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COMPUTER TOMOGRAPHY OF ELECTRONICS

Richard H. Bossi
Robert J. Kruse
Benjamin W. Knutson

Boeing Aerospace Company
P. O. Box 3999
Seattle WA 98124

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WRIGHT RESEARCH AND DEVELOPMENT CENTER
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WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433-6533

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Metals and Ceramics Division

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Metals and Ceramics Division

FOR THE COMMANDER

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The application of Computed Tomography (CT) and laminography has been tested on a variety of electronic components. The effort was performed as a preliminary testing task assignment in the Advanced Development of X-ray Computed Tomography Application program. A key area for testing was printed circuit boards for the inspection of solder bonds and in particular for leadless chip carrier devices. During the course of the task assignment several other categories of electronic devices were examined including transformers, connectors, switches and relays. Seven different CT or laminography systems were used for the scanning. Data from resolution and contrast sensitivity phantoms developed for the program were used to establish quantitative measures of capability used to generate images.

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TASK ASSIGNMENT 1 - ELECTRONICS

(Preliminary Testing)

Interim Technical Report

for
Wright Research and Development Center
Contract #F33615-88-C-5404

Prepared by: Robert J. Kruse
Checked by: Benjamin W. Knutson
Richard H. Bossi
Supervised by: James M. Nelson
Approved by: John E. Shrader

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The application of computed tomography (CT) and laminography has been tested on a variety of electronic components. The effort was performed as a preliminary testing task assignment in the Advanced Development of X-Ray Computed Tomography Application program. A key area for testing was printed circuit boards for the inspection of solder bonds and in particular for leadless chip carrier devices. During the course of the task assignment several other categories of electronic devices were examined including transformers, connectors, switches and relays. Seven different CT or laminography systems were used for the scanning. Data from resolution and contrast sensitivity phantoms developed for the program were used to establish quantitative measures of capability used to generate images.

The results of this preliminary testing of electronics lead to the conclusion that higher resolution CT scanning is needed to resolve details of interest. CT testing on commercially available systems could resolve high contrast details in the range of 2 to 4 lp/mm; however, in many electronic components even finer resolution is needed to detect microcracking, voiding and other features. Further testing on high-resolution systems is recommended. Two areas of immediate potential economic payback for electronics inspection have been identified: the inspection of high volume printed circuit board production using high speed laminography and nondestructive failure analysis studies of components using high-resolution CT.

Key Words

computed tomography
connectors
electronics
inspection
laminography
leadless chip carrier
printed circuit board
relays
solder
surface mount technology
switches
transformers
X-ray

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1.0 INTRODUCTION

The goal of the Advanced Development of X-ray Computed Tomography Applications demonstration (CTAD) program is to evaluate inspection applications for which computed tomography (CT) can provide a cost-effective means of inspecting aircraft/aerospace components. The program is task assigned so that specific CT applications or application areas can be addressed in separate task assigned projects. Under the program, candidate hardware is selected for testing that offers potential for return on investment (ROI) for the nondestructive evaluation system and operation. Three categories of task assignment are employed in the program: 1) Preliminary Tests where a variety of parts and components in an application area are evaluated for their suitability to CT examinations for their inspection; 2) Final tests where one or a few components are selected for detailed testing of CT capability to detect and quantify defects; and 3) Demonstrations where the economic viability of CT to the inspection problem are analyzed and the results presented to government and industry.

X-ray computed tomography (CT) is a powerful nondestructive evaluation technique that was conceived in the early 1960's and has been developing rapidly ever since. CT uses penetrating radiation from many angles to reconstruct image cross sections of an object. The clear images of an interior plane of an object are achieved without the confusion of superimposed features often found with conventional film radiography. CT can provide quantitative information about the density and dimensions of features imaged.

Although CT has been predominantly applied to medicine, industrial applications have been growing over the past decade. Medical systems are designed for high throughput and low dosages specifically for humans and human-sized objects. These systems can be applied to industrial objects that have low atomic number and less than one-half meter (19.7 inches) diameter. Industrial CT systems do not have dosage and size constraints. They are built in a wide range of sizes, from the inspection of small jet engine turbine blades using mid-energy (hundreds of keV) X-ray sources to large ICBM missiles requiring high (MeV level) X-ray energies. Industrial CT systems generally have much less throughput than medical systems. The CTAD program utilizes a wide range of CT systems, both medical and industrial. CT systems offer source energy levels in roughly three categories: low (up to 150 kV), medium (up to 420 kV) and high (2 to 16 MeV).

1.1 Scope

This task assignment, designated "Task 1 - Electronics", is a preliminary testing task directed at the inspection of electrical devices. This report discusses the items selected for testing, the testing, the results of testing, and the conclusions drawn. Included in this study are surface mounted electronic devices on multilayer circuit boards, relays, transformer cores, connectors, and microwave/RF components. Items were selected for testing on the basis of the type of part (density characteristics and complexity), relative cost of the part and the part to its application, current inspection techniques used on the part, and resolution requirements.

A number of different CT machines were used in the course of this task assignment. Identical resolution and contrast sensitivity phantoms were used on each CT machine employed to provide a quantitative measure to assess the image quality of scans obtained. Images reported in this task assignment are designated not by the CT machine brand name utilized, but instead by a system label that is correlated to phantom measurements of resolution and contrast sensitivity levels. The images selected are some of the more informative views of the numerous scans taken in this task effort.

The use of laminographic techniques for inspection was included in the scope of this task assignment because printed circuit boards have a planar geometry that is not necessarily well suited to the CT data acquisition technique. Laminography (body section tomography) uses digital X-ray images taken at several angles to reconstruct focussed depth planes in the object, while defocussing undesired planes.

1.2 Objectives

The goal of the electronics testing was to establish a representative data base of CT and laminographic scans on electronic components. From this data base and knowledge of the economics of part manufacturing and inspection, follow-on tests would be recommended.

2.0 TEST PLAN

The Task 1 test plan called for the acquisition of test samples, CT and laminographic scanning, and evaluation. Electronic test samples were generally categorized into transformers, circuit boards, connectors, and switches and relays. While some circuit board test specimens were specifically manufactured for testing, contacts throughout Boeing and outside of Boeing were made to obtain appropriate test samples. Contacts were established in areas such as Manufacturing Research & Development, Parts Materials & Processes, and Quality Assurance Research & Development. Contacts were found that specialized in magnetics, connectors, printed circuit boards, sensors, relays, and other miscellaneous areas. Meetings were held with members of various programs to introduce the CTAD effort and solicit their input. Several variations of components were supplied by each group, some with known defects and some without. The components were initially screened by evaluating their individual replacement cost and relative criticality to the system in which they fit. Figure 2.0-1 describes the evaluation scheme devised for assigning the relative criticality of components to the mission.

Mission Critical:
Success of the mission (including human survival) is directly linked to the faultless operation of the component. Risks include high cost payloads, and human life. Cost of the component is figured in with the success of the mission. Using CT for inspection may provide a very high payback.

Mission Essential:
Proper operation is essential; however, it is backed up by a redundant system which reduces criticality. Cost of the component,inspection and labor may be figured in with some percentage of the mission success. The use of CT for inspection may provide a very high payback.

High Reliability:
High reliability is desired when failure of the component will not necessarily cause the mission to fail and it is backed up by several redundant systems. Cost of the component is nominal and it is replaced without too much trouble. The use of CT for inspection is questionable.

Reliable:
Nominal reliability is desired and expected; however, failure of the component will minimally affect the mission and will not be a major issue. Redundancy and low replacement cost do not justify the use of CT for inspection purposes.

Figure 2.0-1 Component criticality rating

The preliminary CT study involved selected samples, some of which are shown in Figure 2.0-2 below. The costs and functions varied widely as did their individual criticality rating.

Component	Replacement Cost	Aircraft/Equip. Used on	Criticality Rating
Power Transformer	$5000	E-6, E-3A Avionics	Mission Critical
High Grade Toggle Switch	$1500	Fighter Aircraft Shuttle	Mission Critical
Computer PC Boards	$10,000	All Aircraft Avionics	Mission Essential
RF Cable & Connector	$2000	Communications Voice, Data	Mission Essential
Cable Connector	$200	All Aircraft	High Reliability
High Grade Relay	$100	All Aircraft	High Reliability

Figure 2.0-2 Component criticality chart

2.1 Testing Operation Schedule

The inspection schedule followed for electronics is shown in Figure 2.1-1. Systems were visited based on availability. Components were scanned according to their suitability to the system configuration and resolution. Last minute scans were conducted on the newly developed GE XIM-6 and ICT systems. Four Pi also performed a few complimentary circuit board scans on the 3-DX laminography system. Scan trips were planned for the ARACOR Tomoscope, GE XIM-6 (with high-resolution mode), and Four Pi but were never taken due to delayed development schedules and other complications.

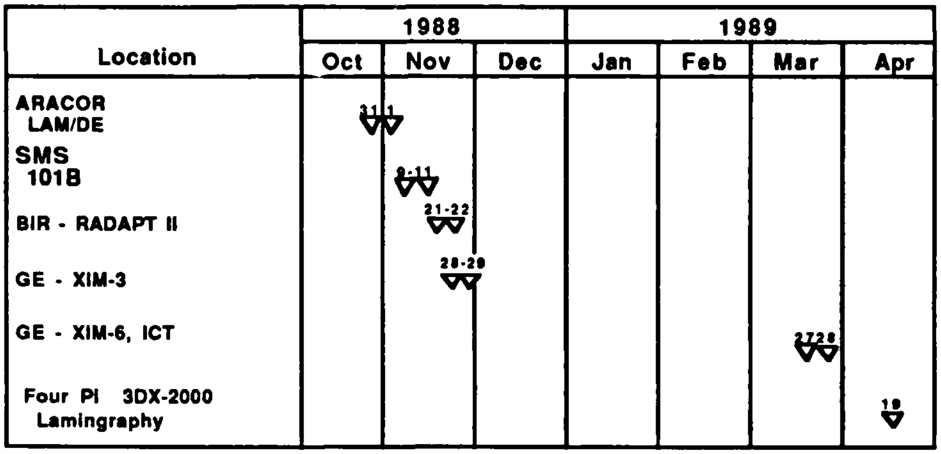


Figure 2.1-1 Task 1 CT inspection schedule

2.2 System Performance

For the inspection of electronics both conventional CT and laminography (body section tomography) were considered. Conventional CT uses data taken in a 360 degree coverage about the object. Laminography uses data from digital radiographs at several angles to the plane of the part surface. The data is manipulated to focus at planes of interest in the object while blurring planes above and below the focussed plane. When a CT machine is reprogrammed for laminography the blurring will occur in only one direction because the digital radiograph is taken with a slit source and angulation can only occur in the plane of the slit. Special purpose machines designed for laminography (but not CT) can blur in two directions. Laminography is generally useful on planar (flat) objects while CT is useful on volumetric objects.

The nonexistence of universally accepted and certified CT standards required that a set of custom phantoms be developed as test standards. The Appendix discusses the phantoms. These test standards provide a measure of the spatial and contrast resolution of each system. Because each system has many variables to consider when evaluating spatial and contrast resolution, any conclusions drawn from the phantoms test results require careful analysis before judgement is made.

Figure 2.2-1 shows a sample of the data obtained from each system with the system names left anonymous. This chart shows a comparison between systems and their ability to image a steel/acrylic line pair resolution standard with the relative modulations and the signal-to-noise level shown. To a first approximation this is meant to indicate the general resolution and signal/noise needed to create the image. However, it is only a rough approximation because actual images may be obtained at different slice widths, fields of view and integration times than those used for the data in Figure 2.2-1 data.

System	Energy KeV/mA	Slice Thickness	Scan Time	Spatial Resolution: Steel Std. Field of View	% Modulation 1 Lp/mm	2 Lp/mm	4 Lp/mm	Signal to Noise Al Std. (Center)	Average Cost per Image
A	420 / 4.0	1.5 mm 15 mm	30 min.	60 mm	55 %	0 %	0 %	17 (1) 73 (1)	$150
B	420/ 3.0	0.25 mm 0.10 mm 0.10 mm	90 min. 11 min. 4.5 min.	50 mm	85 % 75 % 70 %	50 % 33 % 30 %	4 % 3 % -----	6 (1)	$300 $ 65 $ 30
C	300 / 5.0	1.0 mm	12 min.	80 mm	46 %	10 %	0 %	11 (1) 49 (2)	$125
D	420/ 3.0	0.25 mm	1.5 min.	64 mm	58 %	20 %	0 %	25 (2)	$ 15
E	420/ 3.0	0.25 mm	0.5 min.	64 mm	57 %	7 %	0 %	4 (1)	$ 8
F	420/ 3.0	0.25 mm	2.0 min.	64 mm	43 %	6 %	0 %	* *	$ 15
G	160/* *	0.05 mm	0.05 min.	10 mm	* *	* *	* *	* *	* *

* * Data Unavailable

(1) Al Noise Standard 5.5" dia.

(2) Al Noise Standard 2.75" dia.

Figure 2.2-1 CTAD CT system performance data

2.3 High-Resolution Requirements for Electronic Components

Areas of concern in electronics are often found on the microscopic level: solder bond voiding and cracking, potting and hermetic seal cracking, particulate contamination, and micro-alignment of structures (e.g., fiber optics in sensors, 0.38 mm (0.015 inch) wide relay contacts, etc.). Such problems pose a difficult challenge for the resolution capability of conventional CT systems (medical and 'typical' industrial). High-resolution inspection is needed for these concerns.

The resolution of a CT system is governed by the X-ray optics of the system design but is also strongly affected by the data acquisition. Some CT systems can be modified with minimal effort to obtain an image with higher resolution by increasing the amount of information received at the detectors for each object volume element by oversampling or decreasing the rotation scan intervals (thus increasing the samples) by an even factor of 2 or 4. Scans were taken on systems with the oversampling high-resolution feature and an increase in both spatial and contrast resolution was achieved as expected. One disadvantage to oversampling is that the accumulation of 2 or 4 times the information takes at least that much longer to perform and reconstruct.

Another means of high-resolution CT scanning is to modify the system X-ray optics where the detector size is decreased and/or the X-ray source size is decreased, such as with a micro-focal source. Systems of this type are currently under development.

In high-resolution imaging using large reconstruction matrices (1024 x 1024 or 2048 x 2048), the video terminals can also limit the sensitivity to detail in the image. The terminals are limited in the amount of pixel information that can be displayed and often data has to be masked, averaged, interpolated, or deleted. While zoom displays are the common solution, the displayed field of view is restricted which can inhibit interpretation.

2.4 Component Selection

During scanning operations resolution standards helped to determine the limits of the various CT systems. Components were chosen for tests that were suitable to the inspection capability of the system. Components were also chosen (or altered) to fit within the field of view of most of the systems. In the case of circuit board testing, test boards were designed with defects and built 50 mm x 50 mm (2 inches x 2 inches), thus limiting the aspect ratio and reducing image artifacts.

Many components were scanned during the course of this task assignment. Some components were scanned on more systems than others. The images chosen for this report were the ones which showed the most features (with regards to the individual inspection requirements of the component) and image clarity. In some instances the performance of two or more systems was very similar, but image reproduction differed and the clearer image was chosen for inclusion in this report.

2.5 Image Reproduction

All systems displayed their data information on a high-resolution video terminal but hard copy image reproduction techniques varied. Some systems used standard black and white thermal printers, while other systems used black and white or color laser printers. The best reproductions were obtained by a film recorder or by manually photographing the video terminal; however, these options were not always available. This report uses 3rd, 4th or greater generation images and does not give justice to the images as seen on the video terminal of the actual system.

3.0 COMPONENT TESTING AND RESULTS

The selection of electrical components to test was intentionally limited. However, components and structures which were representative of various component sizes and inspection requirements were used. The following sections will describe in detail each of the components chosen, a description of the inspection issue, current inspection techniques, and criticality of the part in terms of mission requirements and cost.

Components scanned were grouped into the following categories:

(1) Transformers and Magnetic Cores
(2) Circuit Boards
(3) Switches and Relays
(4) Connectors
(5) Miscellaneous Components (Temperature Probe).

3.1 Transformers and Magnetic Cores

Transformers are widely used in aircraft and often are the heart of an electrical power system and their failure could be severely detrimental to an aircraft and its mission. Transformers installed in aircraft are made either by transformer vendors or by the aircraft manufacturer in clean room conditions (class 200,000 or better) and require certification before being used. Part of the qualification test certification requires that the transformers undergo electrical testing while under a thermal or vibration testing. Because many of the devices are contained in a potting compound as a hermetic seal, tests are made to determine whether the potting compound has air voids and resists cracking. Should a crack emanating from the surface (and therefore defeating the hermetic seal) find its way to the core, it could allow moisture to enter. This would result in the corrosion of the steel lamination core thus degrading its life and perhaps causing a power failure. A primary transformer that fails in a power supply could have catastrophic results.

Another area of concern for transformers is the alignment of the core components. The transformer core transports the flux current which transfers electrical energy between windings. Should the flux path become disrupted (from corrosion) or even be slightly misaligned it would lead to a decrease in the amount of available flux. This decrease in flux will reduce efficiency of the transformer and, in the case of corrosion, cause sporadic operation. Should the power supply fail to regulate the variation in transformer output, the faulty unit may affect components dependent upon it (i.e., avionics, computers, etc.).

CT scanning of transformers was limited to the inspection of potting and core alignment. Scans were taken on transformers of various sizes and compositions ranging in cost from $700 to $5000. Their criticality to the mission was, in some cases, estimated for similar transformers to be used in mission critical situations.

3.1.1 Selected Test Transformers

Several samples of defective transformers and magnetic cores were obtained from Boeing sources. The components ranged from a transformer weighing 2.3 kg (5 lbs) tc very small wound toroidial cores weighing but a few grams. The two large transformers obtained were designed for the E-6 program and deliver the main three-phase current for the avionics circuit boards. One of the transformers failed a functional test and is suspected of having internally disconnected wires. It is covered with a black resin-like potting material and weighs about 1kg (2 lbs). The other transformer was potted in a small rounded box, was slightly larger than the previous transformer, and weighs about 2.3 kg (5 lbs). This transformer was suspected of having micro-cracking in the potting compound originating from the surface and extending towards the transformer core. The cost of both transformers has been estimated to be $5000 for the production and testing of a deliverable unit.

3.1.2 Current Inspection Methods

The current inspection method involves 100 percent functional testing of the electrical characteristics and approximately 10 - 20 percent life-cycle testing. A life-cycle test may consist of vibration testing, and 1000 hours of continuous thermal cycling and environmental testing. During the testing, the part may also be tested with a fungicide or corrosive agent as well. The part is then sectioned in specified locations, polished, and inspected for micro-cracking, shrinkage of the potting material and corrosion of the core. This is a very timely and expensive process and may take several weeks for a newly designed part to pass its certification tests. The process of inspecting for cracks is difficult. The component is likely to be sectioned with a diamond or band saw, inducing cracks that are difficult to distinguish from any cracks developed during environmental testing. Often the steel lamination core will unfold and cause more uncertainty. Fracturing of compressed ferrite cores during sectioning is an additional uncertainty. An obvious disadvantage is that only the information available in the section location is assessed. Also, the part is obviously destroyed in this sampling inspection approach.

3.1.3 Test Components

3.1.3.1 Component #1: 'E' Core Steel Lamination Transformer

The 'E' core transformer type in Figure 3.1-1 is shown unpotted in Figure 3.1-2. Scan slices were taken in the orientation as shown by plane A. One area of interest in this slice is to identify the butting of the steel laminations beneath the coil. Misaligned laminations causes decreased efficiency of the transformer and may lead to a reduction in life expectancy of the part.

The image seen in Figure 3.1-3, taken on System B, clearly defined the individual 26 gauge (0.404 mm diameter) wires seen in the upper and lower portions of the image The system was unable to define 32 gauge (0.203 mm diameter) wires which are located in a rectangular blurred area above and below the center laminations. Located in the center of the image are the steel laminations. Solder

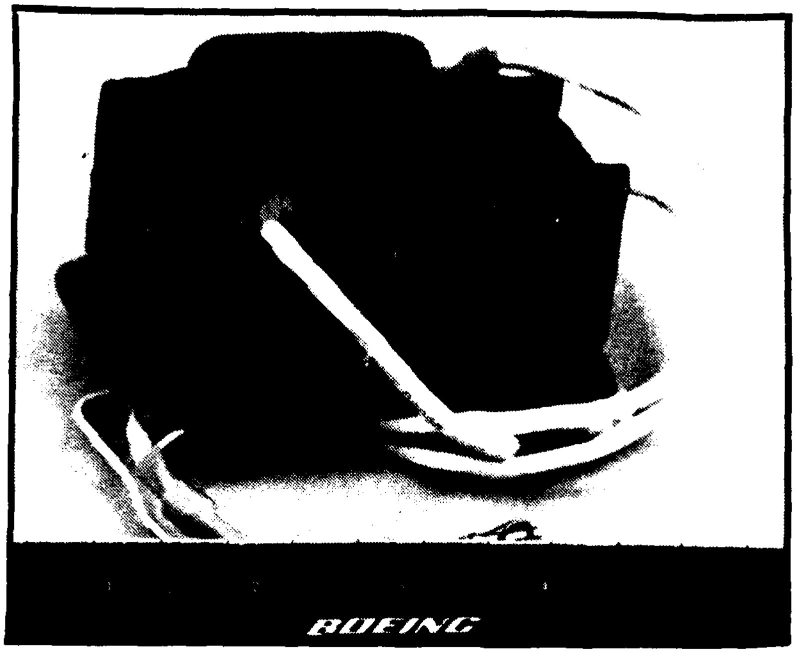


Figure 3.1-1 Steel 'E' core transformer, potted

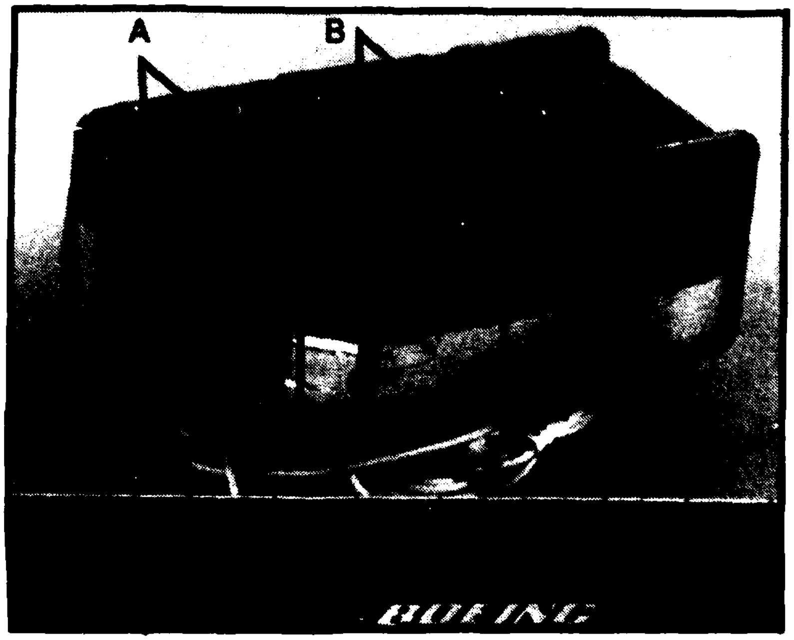


Figure 3.1-2 Steel 'E' core transformer, unpotted

bands used to hold the laminations together are shown to the upper right and lower left of Figure 3.1-3. The core in Figure 3.1-2 uses only 1 band but the core in Figure 3.1-1 has two.

Figure 3.1-4 is a zoom reconstruction (in software - not photographic) of the center of the steel laminations. A slight misalignment of the laminations can be seen along with a small gap visible near the bottom of the image. It appears that the misalignment was caused by the upper band being wrapped tighter than the bottom one.

Figure 3.1-5 is an image of the same component produced on System D, taken at the slice location B in Figure 3.1-2. Major voiding is visible in the potting compound located near the upper windings, although the display contrast level used for this photographic reproduction does not show it. The voiding is a concern with regard to the hermetic seal integrity, electrical conductivity, and thermal conductivity. Also, misalignment can be seen to the far left and far right in the steel lamination groups. This information proved useful to the Boeing Electronics magnetic experts who indicated that they would not have been able to see some of these defects by any of the current inspection methods.

3.1.3.2 Component #2: Compressed Ferrite 'E' Core Transformer

Transformers are also made with cores of compressed ferrite like the one shown in Figure 3.1-6. This transformer has a cost of approximately $700 and is used in a mission-essential application on a major military contract. The destructive failure analysis of this component currently takes 40 hours at a cost of approximately $3800 each.

Images of the transformer shown in Figure 3.1-6 were taken on System E. Figure 3.1-7 is a digital radiograph (similar to a standard film X-ray) showing a profile of the component. CT scan slice locations are indicated. The scan taken in location 2, is shown in Figure 3.1-8. The outline of two ferrite 'E' cores facing each other with 26 gauge (0.404 mm diameter) windings in-between is shown. The uneven winding arrangement is of particular interest. Nothing unusual is seen in the alignment of the two ferrite cores. The image does not appear to have the sensitivity to detect micro-cracking in the ferrite. Micro-cracking is of concern, although none is suspected in this unit.

The scan taken in location 4 in Figure 3.1-9 indicates 'U' shaped voiding beneath the high Z elements (solder). The voiding is detectable in spite of the artifacts. The scan in location 5 seen in Figure 3.1-10, detected potting cracks which ran across the component (left to right) in the upper and lower portions of the image. Although the image contained a partially obscuring artifact ('X' shape, induced by the steel threaded inserts in the corners), the cracking was detected.

3.2 Circuit Boards and Solder Defects

The inspection of electronic assemblies utilizing multilayer and surface-mount technology (SMT) was identified initially as a challenging and much needed

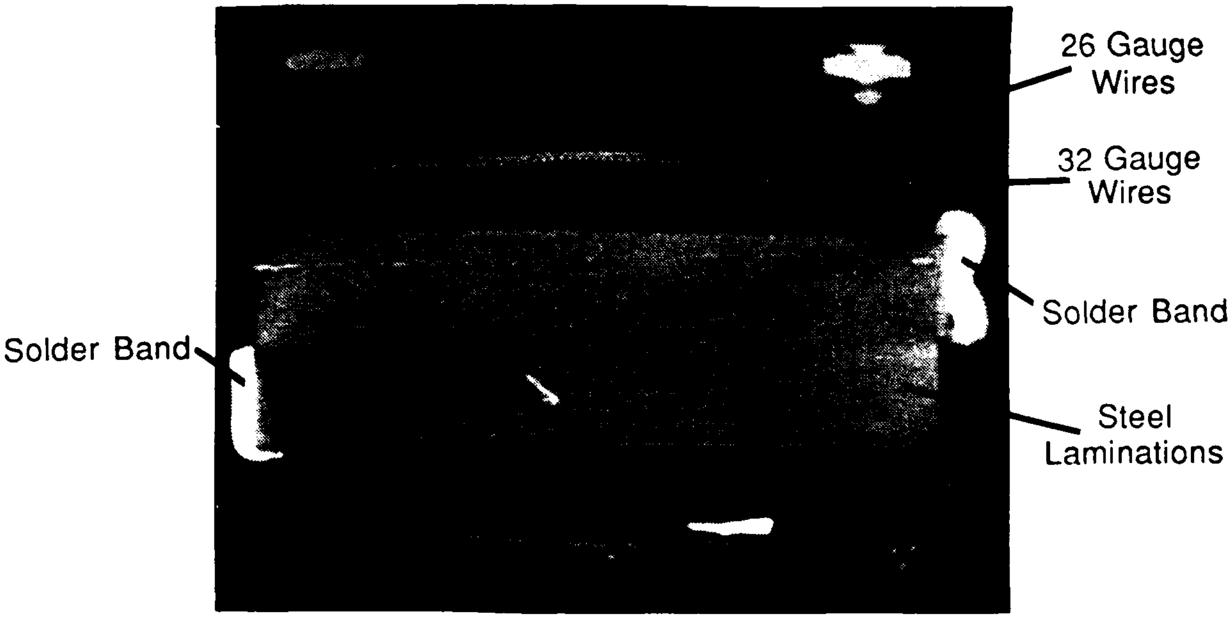


Figure 3.1-3 CT scan of Figure 3.1-1 transformer at slice location A of Figure 3.1-2 from System B

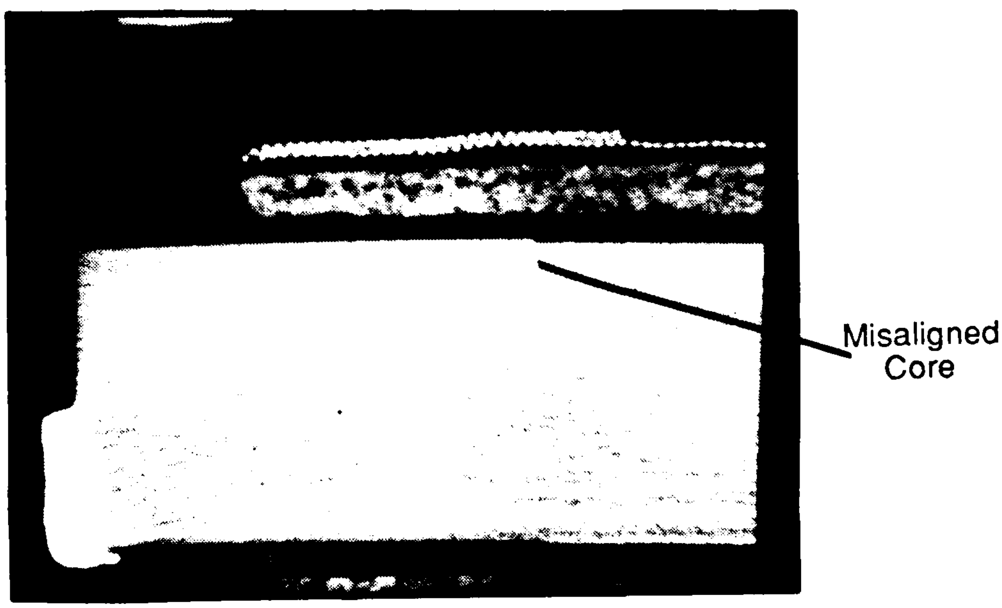


Figure 3.1.4 Zoom reconstruction (in software) of Figure 3.1-3

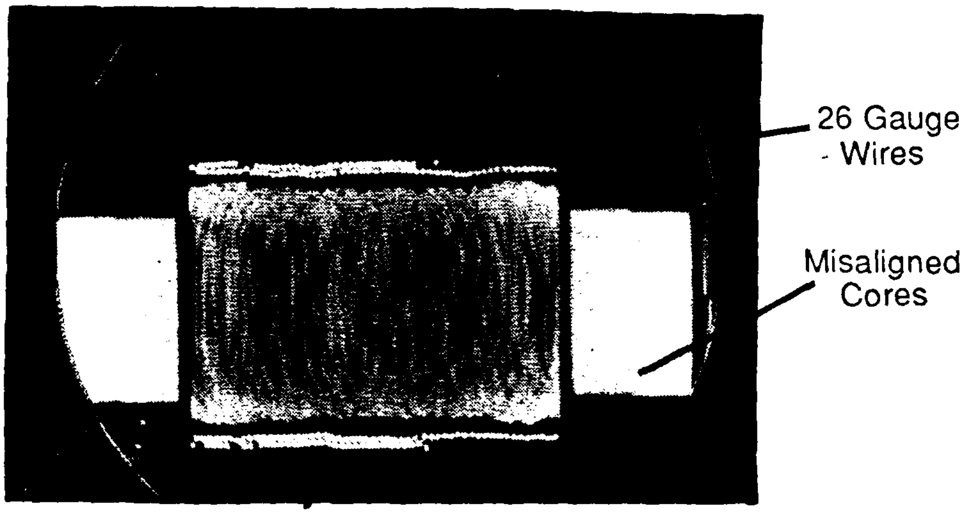


Figure 3.1-5 CT scan of the Figure 3.1-1 transformer at slice location B of Figure 3.1-2 from System D

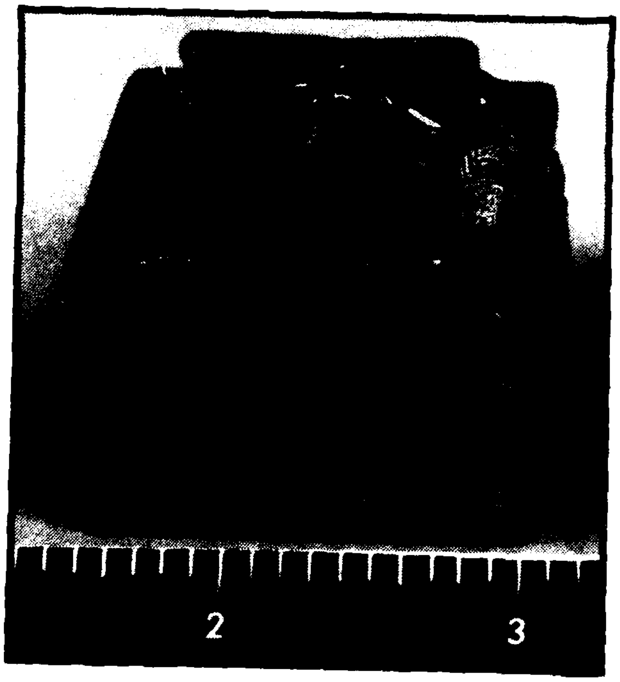


Figure 3.1-6 Compressed ferrite 'E' core transformer

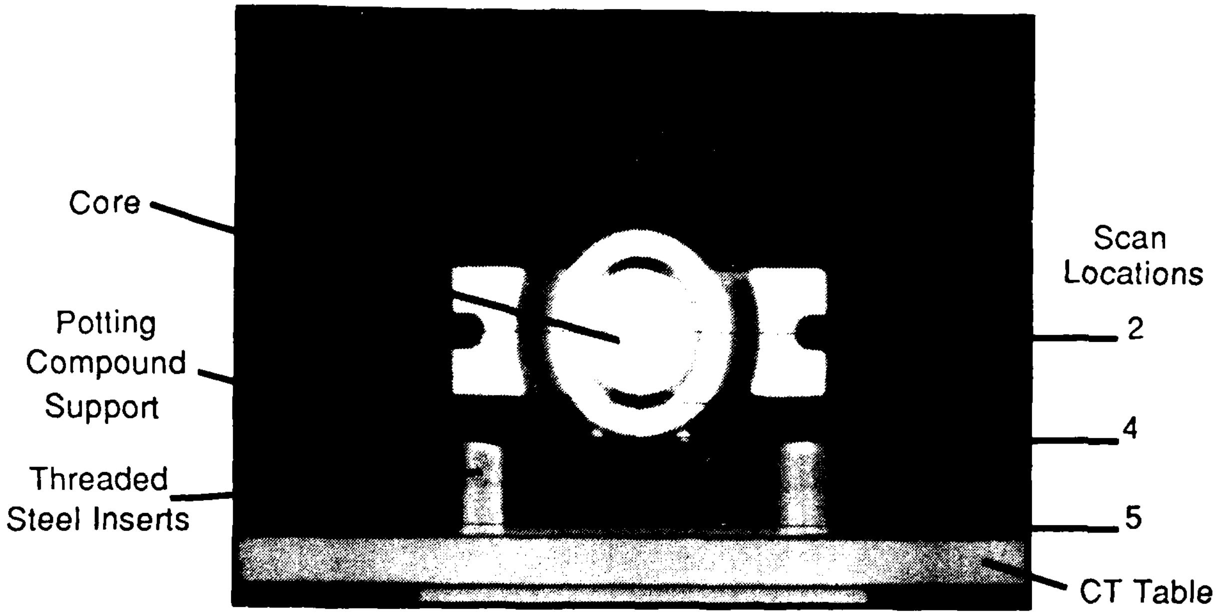


Figure 3.1-7 Digital radiograph of the Figure 3.1-6 transformer from System E

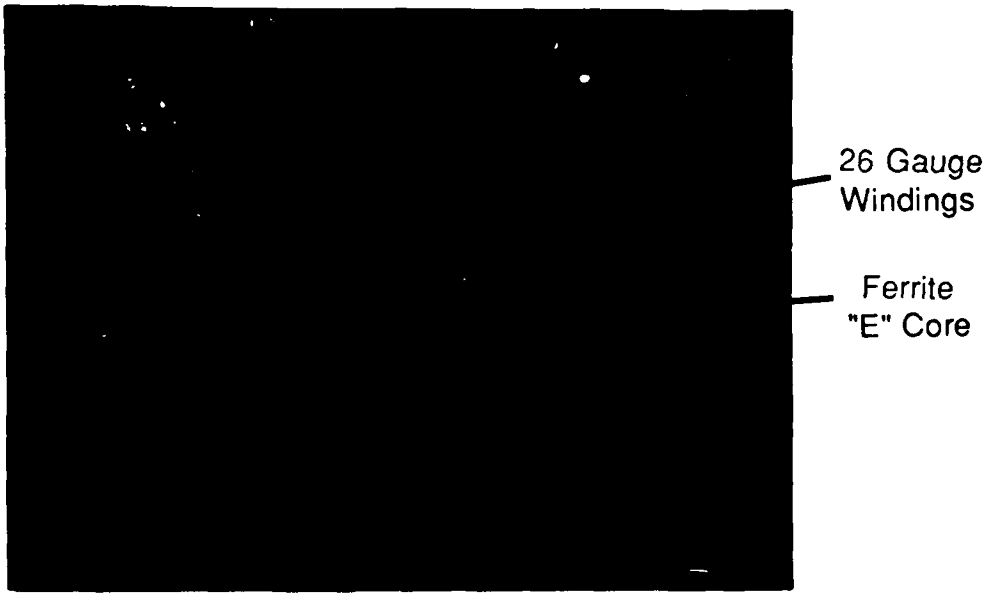


Figure 3.1-8 CT scan of the Figure 3.1-6 transformer at slice location 2 of Figure 3.1-7 from System E

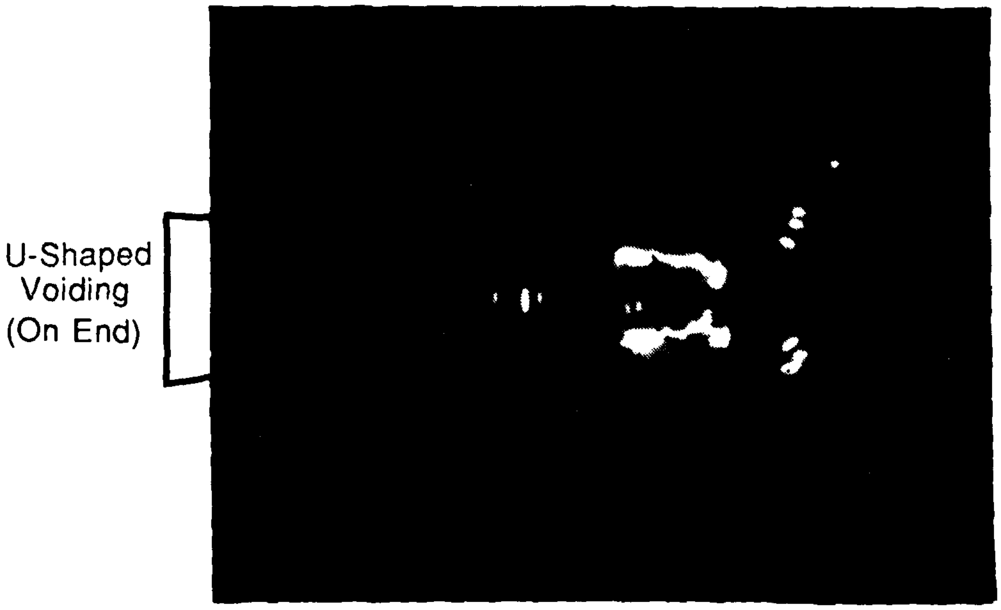


Figure 3.1-9 CT scan of the Figure 3.1-6 transformer at slice location 4 of Figure 3.1-7 from System E

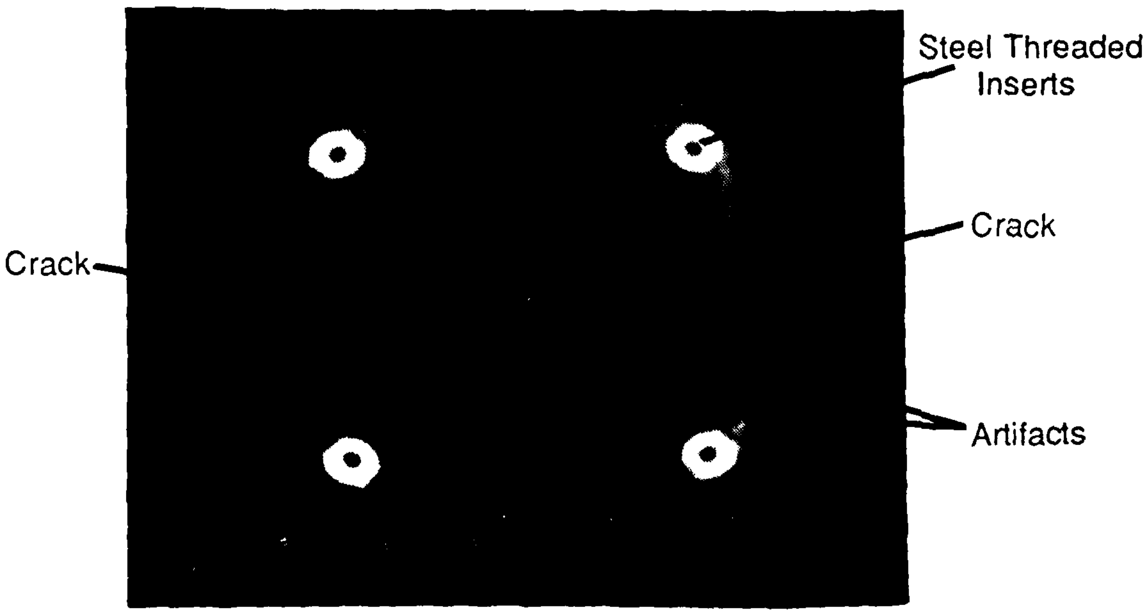


Figure 3.1-10 CT scan of the Figure 3.1-6 transformer at slice location 5 of Figure 3.1-7 from System E

application of NDE technology. The number of interconnections on printed circuit boards (PCB's) have grown in geometric proportions with lead sizes and spacings shrinking from 4 mm (0.100 inch) pitch to 1 mm (0.025 inch) pitch and less. This reduction in lead sizes has opened up an entirely new set of problems when determining solder bond integrity. Similarly, the advent of surface-mount technology incorporates leadless chip carriers (LCC's) with underside metalizations bonded to the pads on the PCB. In these cases, the metalizations are hidden from view and add yet another degree of difficulty to inspecting the bonded area.

PCB designers are being driven to optimize their designs by maximizing their use of available area and ultimately by squeezing in more and more solder connections. This means applying SMT to double-sided boards, often with 12 or more layers utilizing thermal conducting cores for strength and heat dissipation. Thermal cores are typically made of copper, Invar (Ni, Fe, Mg composition), and molybdenum (1.0 -2.5 mm thickness) where the latter two materials severely inhibit the low energy (70 - 120 kV) X-ray penetration of solder joints.

3.2.1 Radiation Effects on Electronics

Inspection of solder joints using X-rays also brings up the issue of the radiation dosage handling capabilities of electronic technologies. Not all electronic technologies react to X-ray radiation in the same way, some are radiation 'hardened' and have the ability to withstand large doses while others exhibit single event upsets at relatively low dose rates. There have been several studies of electronics under electrically biased conditions where the single event upset is measured in real time, but there have been few, if any, studies of electronics in an unbiased state. The chart in Figure 3.2-1 was taken from a paper where the electronic components were in their unbiased state and shows a comparison between technologies and total dose required to cause degradation in performance.

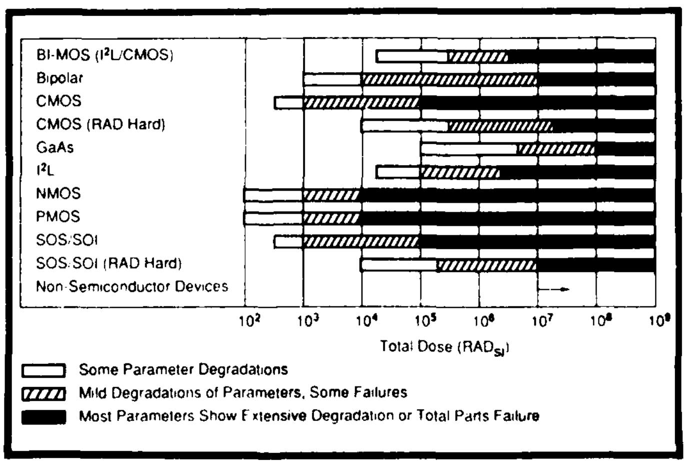


Figure 3.2-1 Total dose radiation analysis of semiconductor technologies*

* Dr. M. Gauthier & A. Dantas, "Radiation-Effects Testing for Space and Military Applications, "*Test and Measurement World*, Cahners Publishing Co., Feb. 1988.

Radiation hardened technologies handle in the order of 10^6 RAD's before most of the component parameters degrade. Other more susceptible technologies may withstand 10^4 RAD's before they exhibit major degradation, although they may beccme slightly affected with as little as 100 RAD's.

Dosimeter tests were conducted during CT tests to attempt to measure the total radiation absorbed dose (RAD) the components received during scanning. Thermo-luminescent dosimeters (TLD's) made of a lithium fluoride compound were calibrated and used to measure the total incident radiation during single and multiple scans. The results varied greatly between systems and components tested, but indicated that on the average, components received 145 RAD's per scan (scan time averaged to 12 minutes with a 420 kVp/ 3.5 mA source). This may be compared to a film chest X-ray of 0.060 RAD's or medical CT chest scan of approximately 5 RAD's.

Although these results are preliminary and deserve additional measurements, they do indicate that there is the possibility of certain susceptible technologies being degraded by extensive CT scanning. Radiation degradation occurs in the components whether or not the boards are biased and in some cases dissipates over time. While it appears that the dose level from CT may be at least an order of magnitude lower than the onset of degradation, further studies should be conducted to assure that the integrity of the components will not be compromised if it is determined that CT is suitable for the inspection of circuit boards.

3.2.2 Solder Defects

Solder defects arise during manufacturing and service where the solder joint may experience any of the following defect and failure phenomena: stresses and strains, thermal and mechanical fatigue, corrosion, electromigration, leaching, creep, intermetallic compound formation, detrimental microstructure development, and joint voiding. Although any of these might have a contribution to the overall performance of the solder joint, it is the visually observable defects that are considered in the production inspection.

Primary defects for visual inspection include insufficient or excess solder, voiding, poor wetting, cracked bonds, solder balls, and excess base metal. The visual inspection for these defects is costly, inconsistent, and often inadequate. A typical military PCB comprised of a 12 layer board and moly core utilizing SMT may cost anywhere from $8,000 to $20,000+, where 5 - 10 percent of the associated cost may go towards solder inspection. The cost per board may seem reasonable if the solder bond integrity is guaranteed, but unfortunately board failures have still occurred in service.

3.2.3 Scanning Tests

Circuit boards were initially scanned using CT, and later imaged using digital laminography. A phantom circuit board was created with simulated solder balls ranging in size from 0.1 to 1.0 mm (0.005-0.040 inches), simulated bridging, and solder voiding on LCC and 'J' leaded devices. The board was designed 50 mm (2 inches) square so that it would fit within the field of view of the available systems. Similarly, a 50 mm (2 inches) square sample of a double-sided 12 layer board with a copper-Invar-copper (CIC) thermal core was acquired and contained solder balls and voiding under several LCC's.

3.2.4 Test Components

3.2.4.1 Circuit Board #1: Military Circuit Board - CT Scanning

The circuit board in Figure 3.2-2 is typical of high-grade military boards and has a value of approximately $5000. Some of the features on the board are the black aluminum frame surrounding the components, several relays (small boxes), the individual components and, of course, solder locations.

Figure 3.2-3 shows a scan that was taken at the upper plane level of the board on System A with a 1.5 mm (0.060 inch) slice thickness. This image is free of major streak artifacts, considering the high aspect ratio of the board the aluminum frame and several high Z solder locations. The system does not have the resolution to identify details about the solder locations like voiding, cracking and solder balls.

A scan taken a few millimeters above the board is shown in Figure 3.2-4, and reveals information about the internal structure of the relays and precision wound resistors (filled in rectangles). It is conceivable to think that a system with improved resolution would be able to scan a circuit board, identify solder location information and also be able to identify defects in components such as relays without removing them from the board (a costly failure analysis procedure which often results in destroying good parts).

3.2.4.2 Circuit Board #2: Phantom Board - CT and Laminography Scanning

The printed circuit board test phantom shown in Figure 3.2-5 proved to be a very useful tool in understanding the basic characteristics in a system's ability to resolve certain features.

A CT scan taken on System C is shown in Figure 3.2-6. This image has heavy artifacts and fails to provide information about bond integrity except solder detection. The system resolved solder balls down to approximately 0.25 mm (0.010 inch) (11 of 13 rows of 3, 10 rows are visible in the Figure 3.2-6 reproduction), where the solder balls ranged from 0.1 to 0.25 mm (0.004 inch to 0.010 inch). Higher energies, improved resolution and/or artifact reduction from the capability of a System C are required for conventional CT inspection to be useful.

A laminogram taken on System B (a system primarily designed for CT, but is reconfigured in software for laminography) is shown in Figure 3.2-7. The laminography image shows significant improvement over the Figure 3.2-6 CT image in solder detection including all 13 rows of solder balls, but was unable to

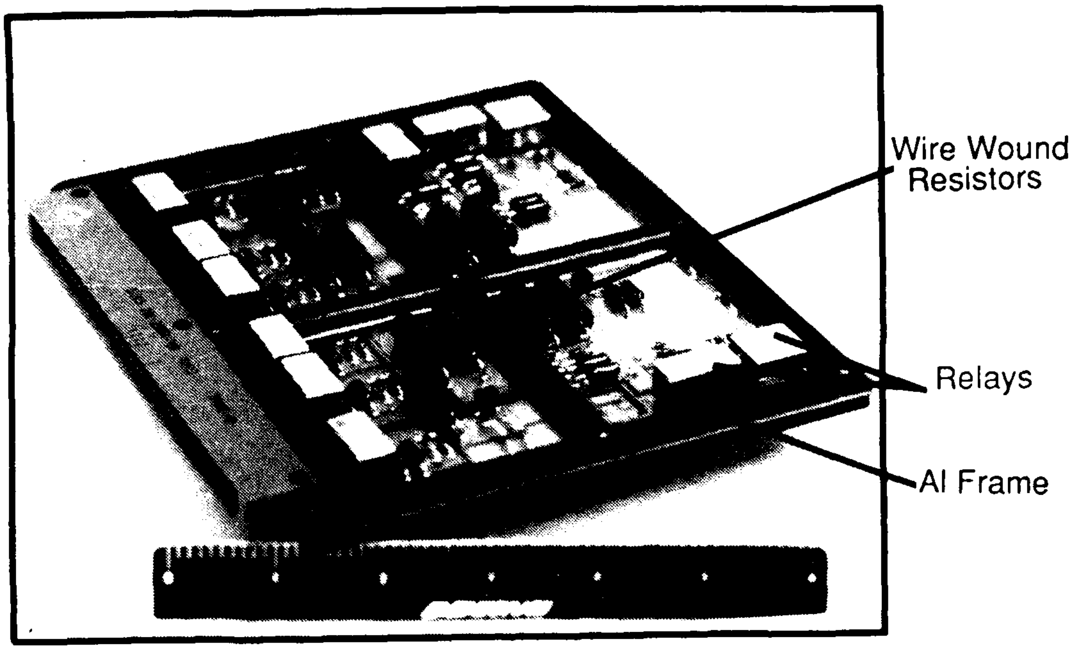


Figure 3.2-2 High grade military circuit board

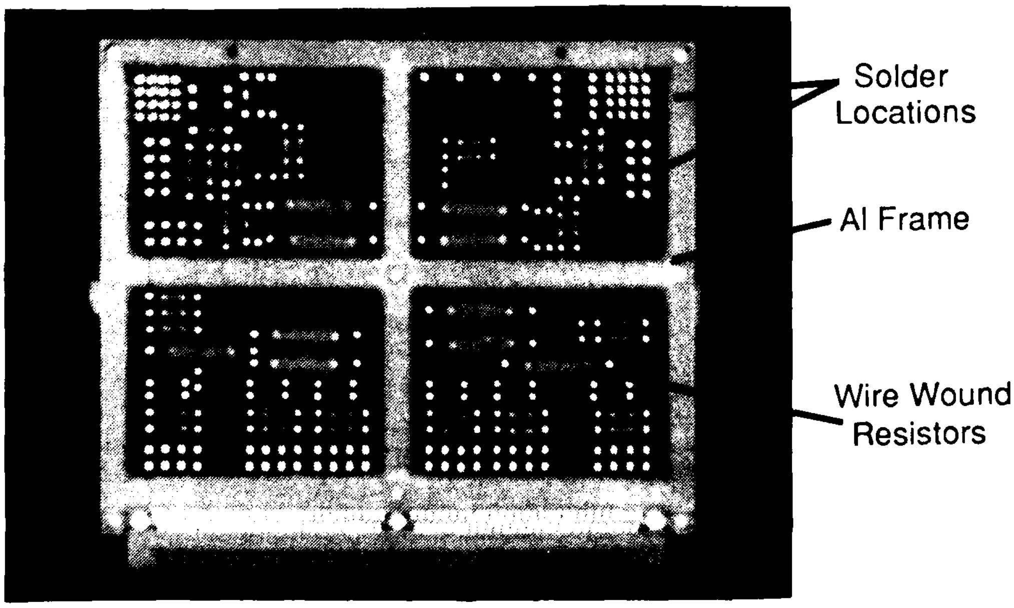


Figure 3.2-3 CT scan of the Figure 3.2-2 circuit board from System A showing solder locations

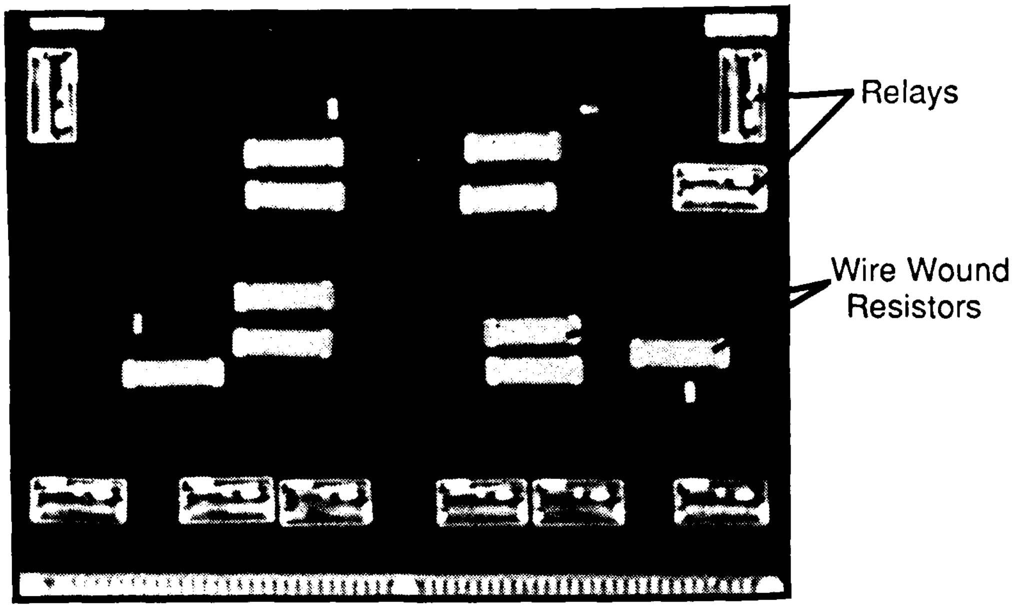


Figure 3.2-4 CT scan of the Figure 3.2-2 circuit board from System A showing the internal structure of the relays

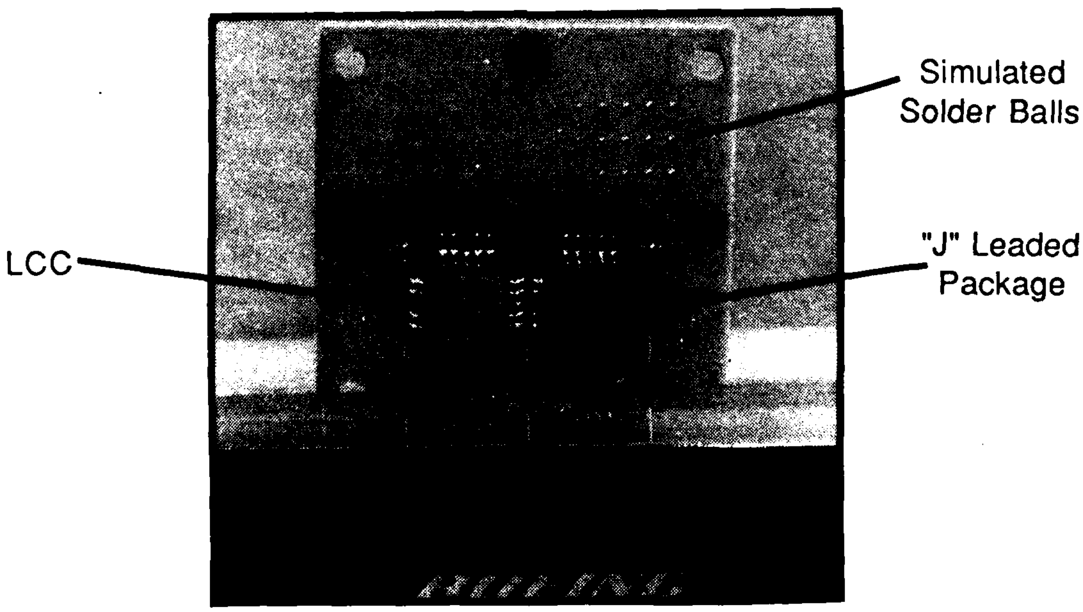


Figure 3.2-5 Printed circuit board test phantom

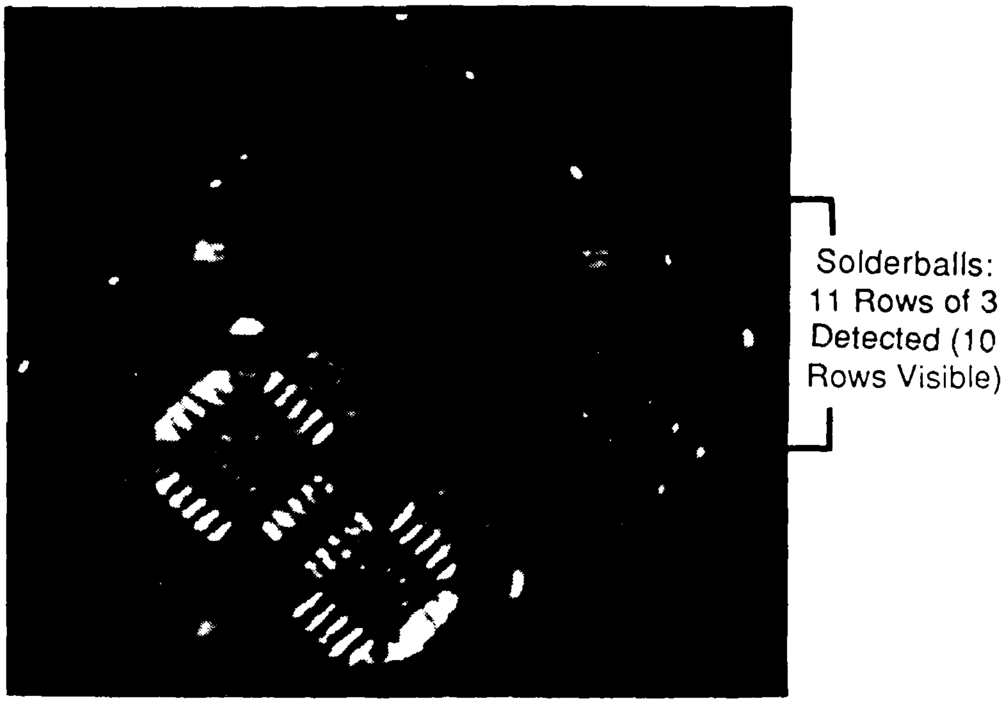


Figure 3.2-6 CT scan of the printed circuit board test phantom from System C

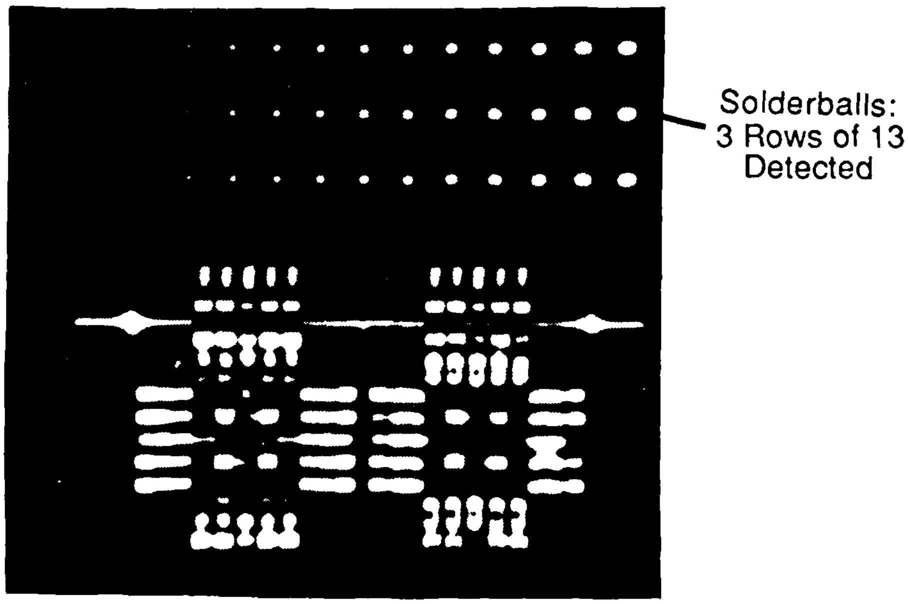


Figure 3.2-7 Laminogram of Figure 3.2-5 board from System B

identify voiding and cracking of solder. Using the image analysis capabilities of System B, the top LCC was enlarged in software and is shown in Figure 3.2-8. Note the differences in the amount of solder contained on the pads.

Laminography was also performed on System G, which is optimized for the high-speed inspection of solder bonds. The image in Figure 3.2-9 shows voiding in the solder joint and a solder ball adjacent to the pad is indicated. Simulated bridging between pads approximately 0.050 mm (0.002 inch) wide was detected by System G and is seen in Figure 3.2-10.

3.2.4.3 Circuit Board #3: 12 Layer CIC Board - Laminography

A more challenging circuit board for X-ray solder inspection is the CIC board produced by Boeing Electronics, a section of which is seen in Figure 3.2-11 (approximately 2 by 2 inches). This board is double-sided with 6 layers to a side and a 1.5 mm (0.060 inch) thermal core made of Invar (atomic number approximately 26). Both sides are populated with gold packaged LCC's with 0.6 mm (0.025 inch) pitch pad spacings. This sample is from a test board with the package lids removed exposing the die cavity. This particular board is a mission-critical main processor board used on SRAM II, V-22, and other programs with a value of over $10,000 each.

Laminography proved to be the more beneficial than CT for imaging boards of this type. Laminography performed on System B is shown in Figure 3.2-12 focussing on the front surface. Although the reproduced photo leaves some features ambiguous, the image clearly outlines the front side of the board as indicated by the solder locations.

Moving through the laminographic data set, the rear side of the board is focussed in Figure 3.2-13, indicating the presence of packages to the right and bottom of the view. Although the images show the ability of System B to perform laminography, they fail to identify the areas of interest: namely defects in the solder.

The CIC board was imaged by System G and a radiograph is shown in Figure 3.2-14. The image shows the superposition of the solder locations on the front and back sides of the board. Although there is major confusion when inspecting for defects, voids in the solder in the range of 0.15 to 0.25 mm (0.006 to 0.010 inches) are readily visible.

Using laminography, the individual sides of the board are brought into focus, clearly separating the solder defects and their locations. System G has the ability to detect voids in solder down to 0.025 mm (0.001 inch) and solder balls as small as 0.025 mm (0.001 inch). Figure 3.2-15 is the front surface of the OIC board, which shows several pads with voiding, and Figure 3.2-16 is the back surface, highlighting several solderballs (but not voiding).

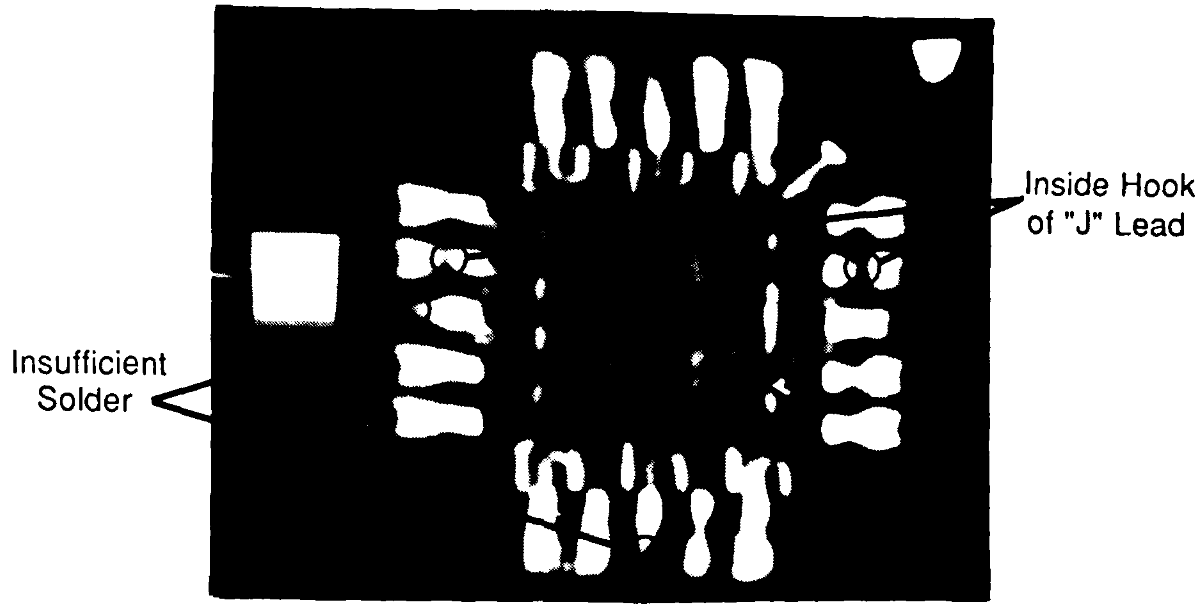


Figure 3.2-8 Enlarged image of top LCC in Figure 3.2-7 from System B

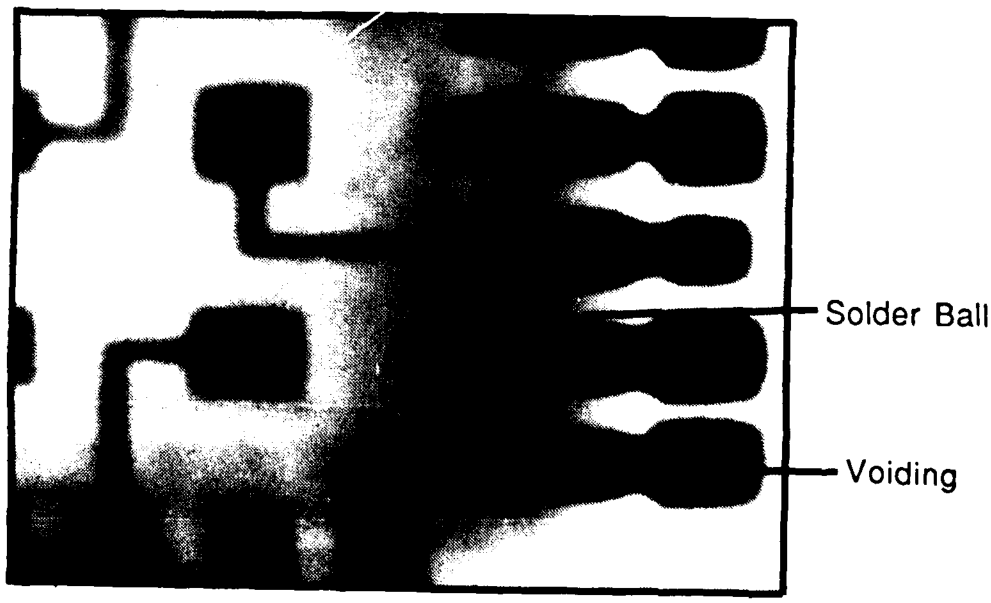


Figure 3.2-9 Laminogram of a portion of LCC from Figure 3.2-5 board from System G

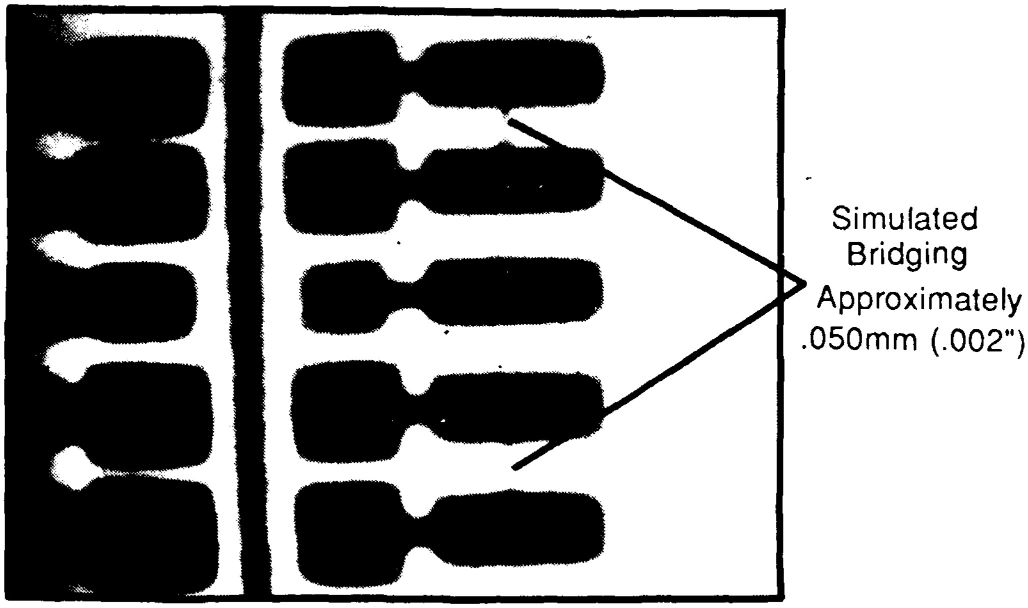


Figure 3.2-10 Laminogram showing bridging from System G

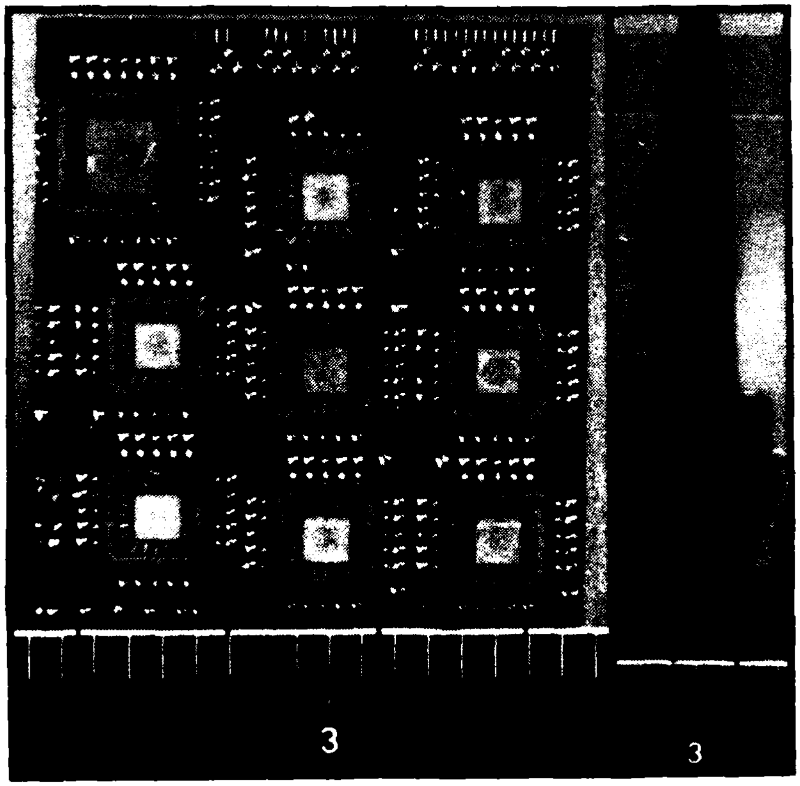


Figure 3.2-11 Twelve layer CIC board section (front and side views)

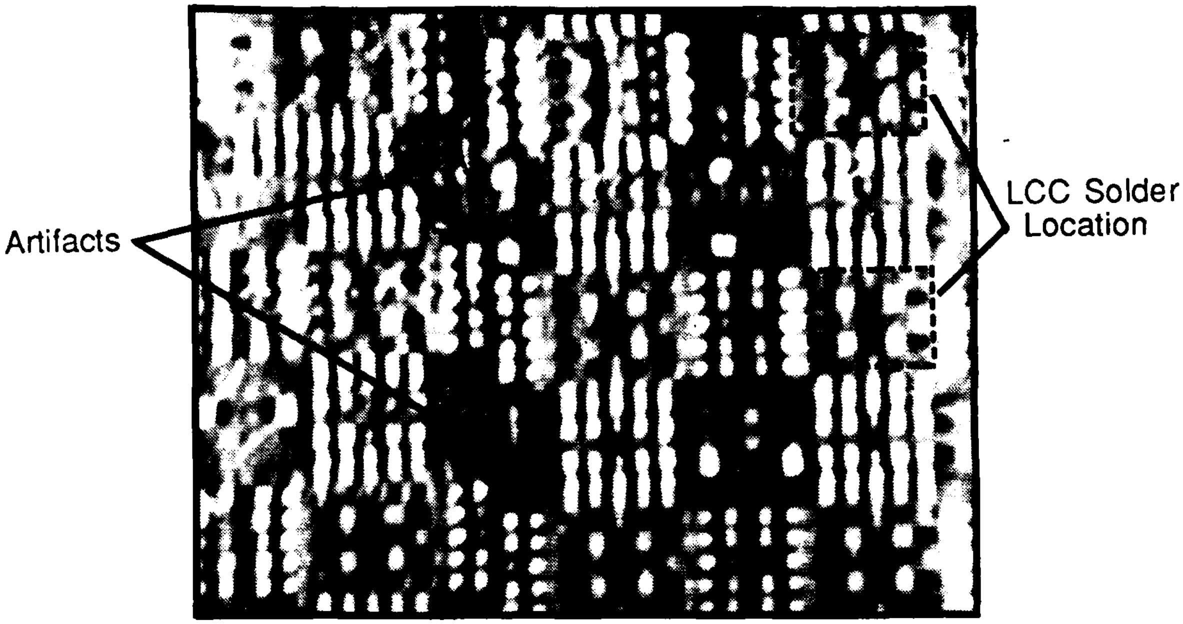


Figure 3.2-12 Laminogram of the front side of the Figure 3.2-11 board from System B

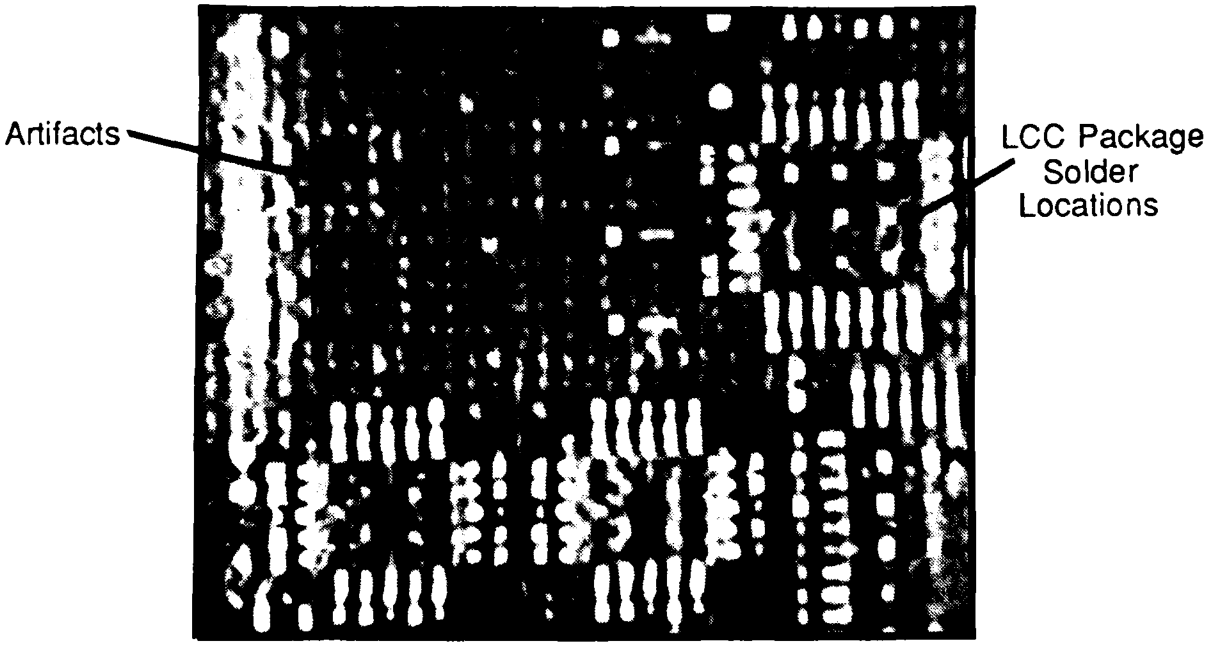


Figure 3.2-13 Laminogram of the rear side of the Figure 3.2-11 board from System B

Figure 3.2-14 Radiograph of a portion of the Figure 3.2-11 board from System G

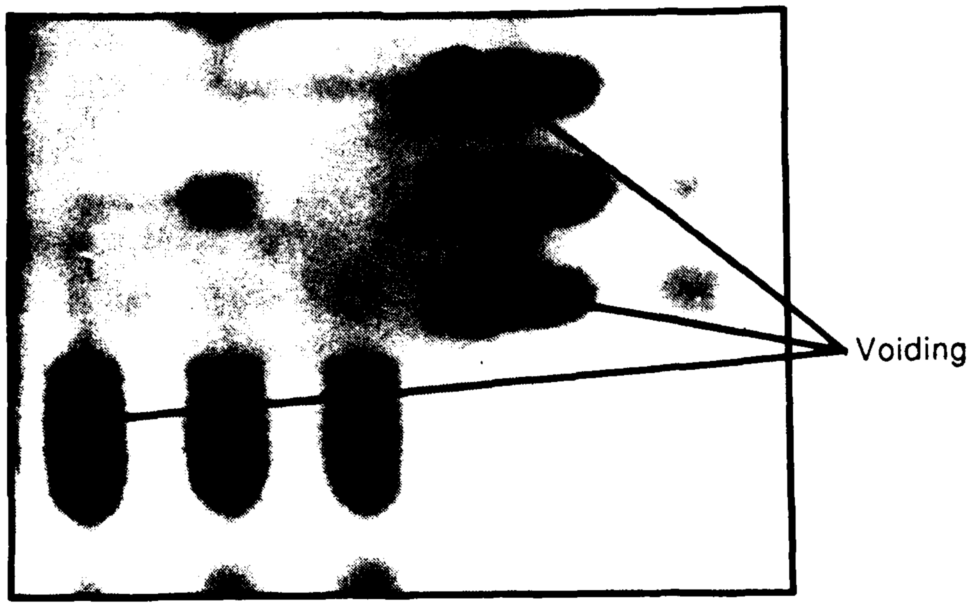


Figure 3.2-15 Laminogram of a portion of the front side of the Figure 3.2-11 board from System G

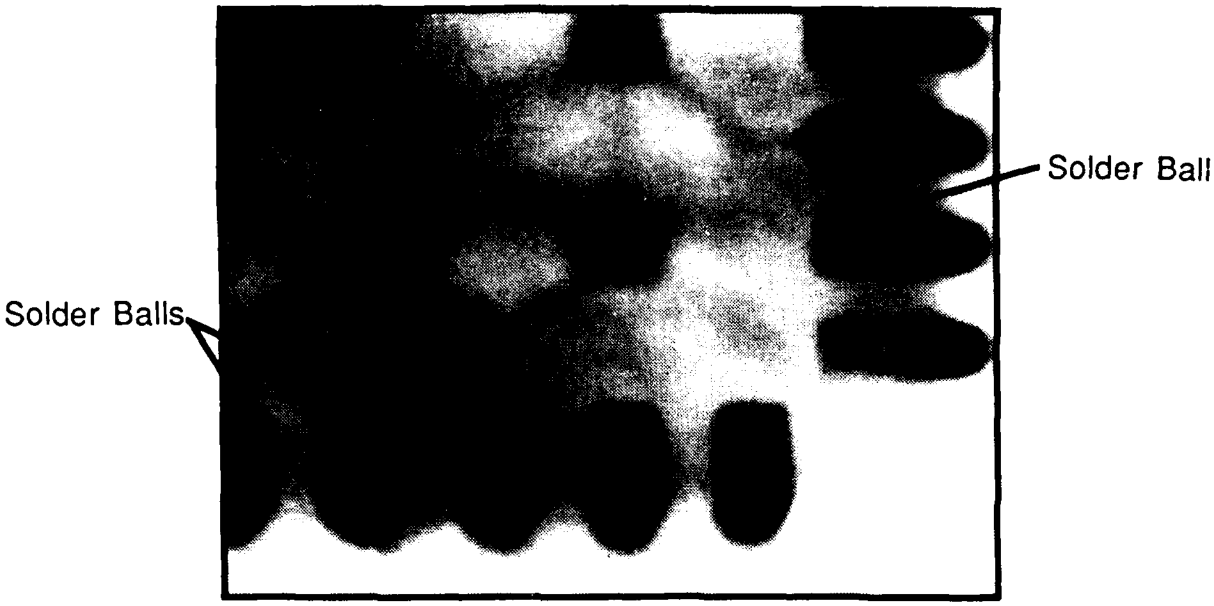


Figure 3.2-16 Laminogram of rear surface of the Figure 3.2-11 board from System G

The inability to image solder defects with laminography on System B may be partly attributed to the fact that System B was not optimized for penetrating tin-lead. By filtering the beam to harden the spectrum the solder inspection may be improved. System G is optimized in this sense for inspecting solder bonds. System G also has a small field of view (10 mm [0.4 inch]) which allows high resolution but requires many exposures to inspect a complete board.

3.3 Switches and Relays

Mechanical devices such as switches and relays have a finite life and are prone to failure due to their nature. A switch and/or relay is required to control primary electrical current flow in the most critical systems on a vehicle. Although precautions are taken in the manufacturing of these items, it is often difficult to predict the longevity of the component without destructive analysis. Likewise, the evaluation of a failed component is equally difficult to complete without a destructive verification which often destroys the evidence.

Switches are the primary interface between a system operator (pilot, navigator, etc.) and the system. They must be extremely reliable. Common problems in defective switches are mechanical failure (structural, springs, contact bending, melting, or fusing etc.), hermetic seal failure, contact corrosion, and particle contamination. Military aircraft and aerospace switches range in cost from $20 to $1500, with applications in uncritical as well as mission critical situations.

Relays have a degree of added complication from switches in that they may be used in mission-critical situations, but are often controlled by another electrical device. Since they are not necessarily located near the system operator, failures may remain undetected depending on the complication of the controlling system. While an operator may suspect a system problem, other areas may receive priority in correcting the situation while the relay remains faulty. A defective relay could conceivably cause a major malfunction in a system yielding a costly and detrimental impact.

Inspection issues for relays are the same as those of the switches and include the concerns for the magnetic components such as magnetic winding and core integrity. Military specification relays can range in cost from $20 to $200 and more depending on the application. Failure analysis of defective relays can require anywhere from 8 to 30+ hours to perform continuity testing, package gas testing, sectioning, dismantling, and documenting. CT scanning was performed on several relays and was able to assess the quality of several features within the relay package such as bent or welded contacts along with other structural information.

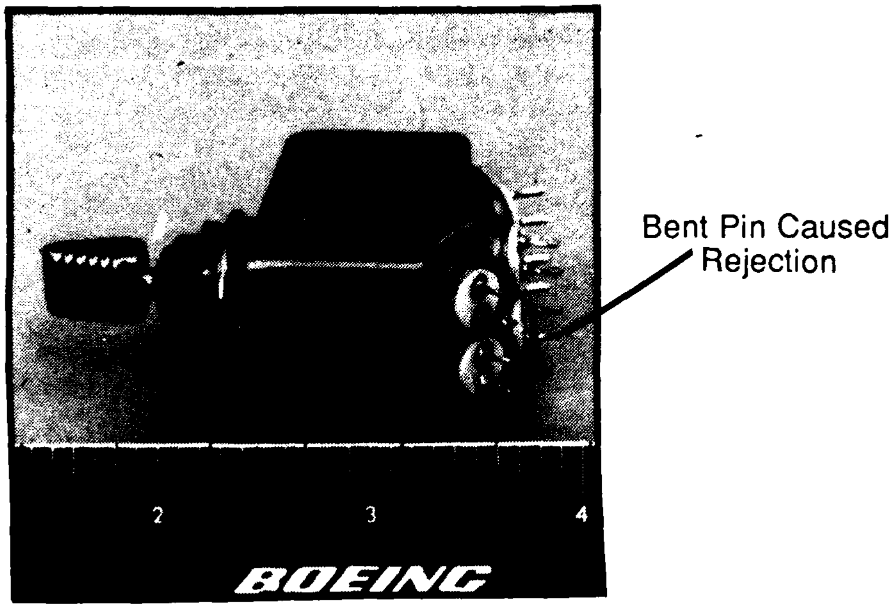


Figure 3.3-1 High grade military switch

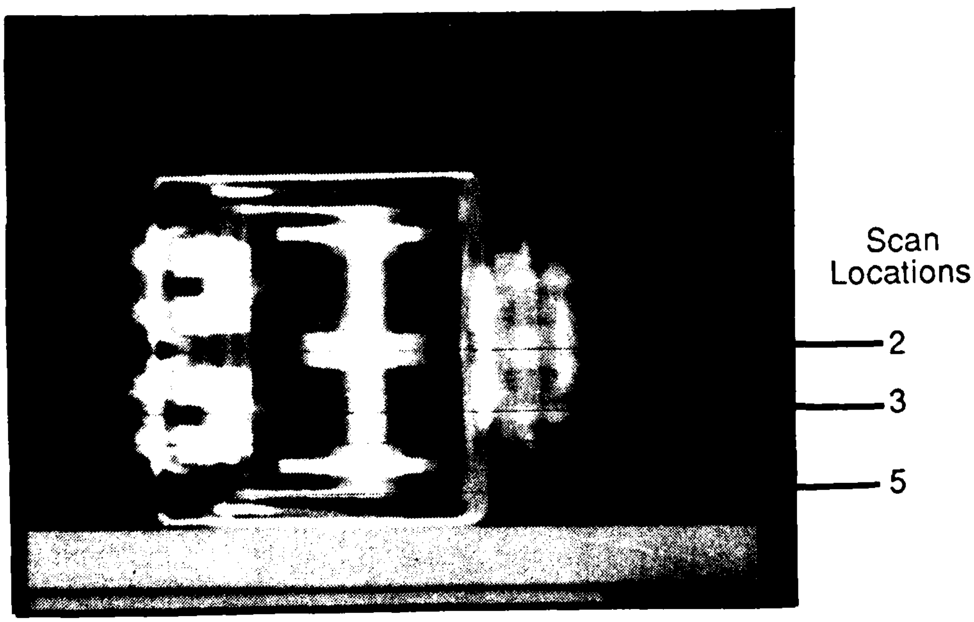


Figure 3.3-2 Digital radiograph of Figure 3.3-1 switch from System E

3.3.1 Test Components

3.3.1.1 High Grade Military Switch

An example of a mission-critical switch, shown in Figure 3.3-1, has a cost of $1500 and is used in the cockpit of a major military aerospace program. Although this component does not have any suspected internal flaws, it was rejected on the basis of having an external pin bent 10 degrees out of tolerance.

A digital radiograph in Figure 3.3-2, taken on System E, indicates the scan planes of the CT images taken. Scan plane #2 is shown in Figure 3.3-3 and identifies the mechanical structure of the toggle handle assembly. Scan plane #3, in Figure 3.3-4, identifies a spring structure in the center and ceramic seals to the left - all possible failure sites.

Taking a scan at location #5 (Figure 3.3-5) clearly displays the lever and spring mechanism - another potential failure mode. Figure 3.3-5 can be compared to Figure 3.3-6, taken on System C, which is similar although the image lacks intensity due to photographic reproduction limitations. Another image taken on System C, shown in Figure 3.3-7, clearly identifies sets of bearings which could be prone to failure as well.

3.3.1.2 RF Relay

A common type of mission essential multipole RF relay used in data/communications transmission is shown in Figure 3.3-8 and has a cost of $700. This particular relay is used in a major military program in a mission-critical application. Engineering spent over 2 man-years analyzing a contact problem which it is felt could have been identified by CT. Plane A in Figure 3.3.-8 indicates the region of interest where defective reed contacts are contained.

Figure 3.3-9 is an exploded view drawing of the relay. A scan taken on System E, shown in Figure 3.3-10, shows 4 good contacts and one missing (the relay has 5 good contacts, as seen in Figure 3.3-9). Figure 3.3-11 identifies the defective contact, which might be difficult to determine using destructive analysis due to the contact size and orientation within the stainless steel enclosure.

Although one might recommend an electrical functional test to identify which pole is faulty, it would be more time consuming to determine whether the fault is in the electromagnet, springs, insulators, contacts, or connectors. These images clearly indicate that the problem is mechanical. CT analysis could be used by Receiving and Inspection to return the component to the vendor before any production and testing costs were incurred. Another option is to conduct an electrical test in conjunction with CT scanning to better isolate the fault.

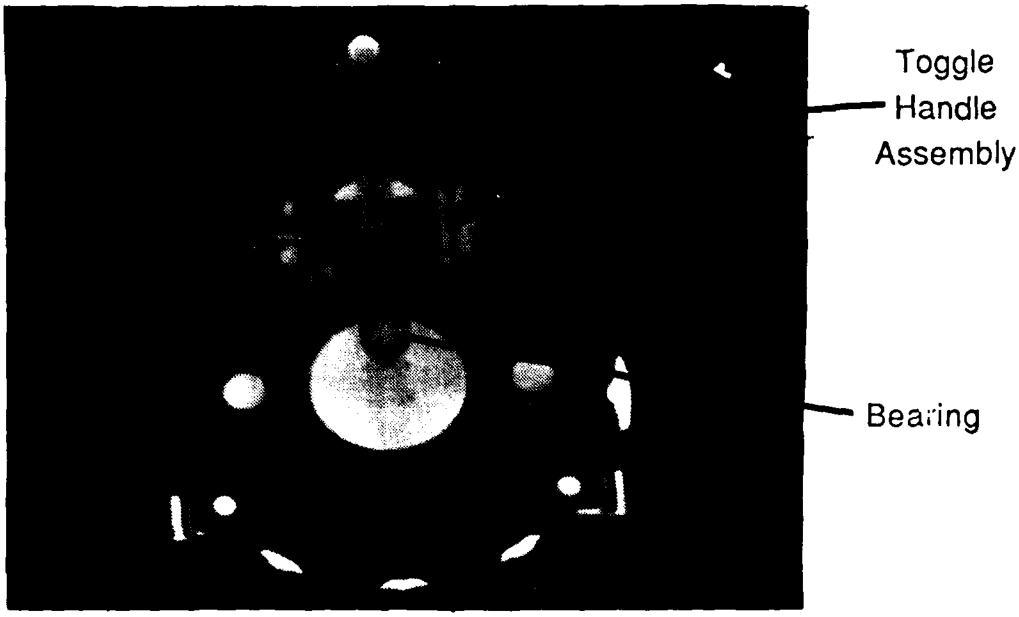


Figure 3.3-3 CT image at scan plane #2 in Figure 3.3-2 for the Figure 3.3-1 switch from System E

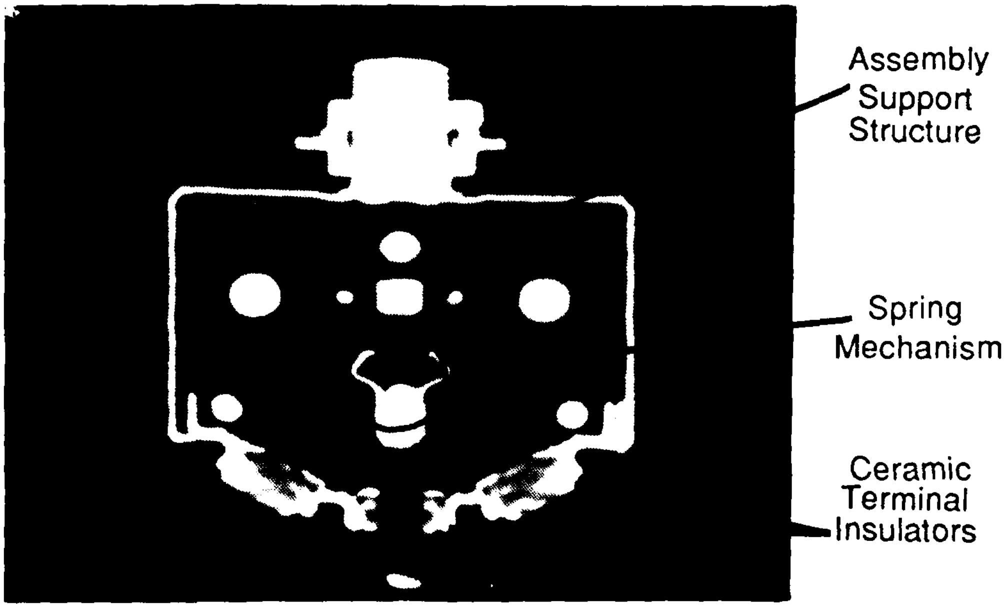


Figure 3.3-4 CT image at scan plane #3 in Figure 3.3-2 for the Figure 3.3-1 switch from System E

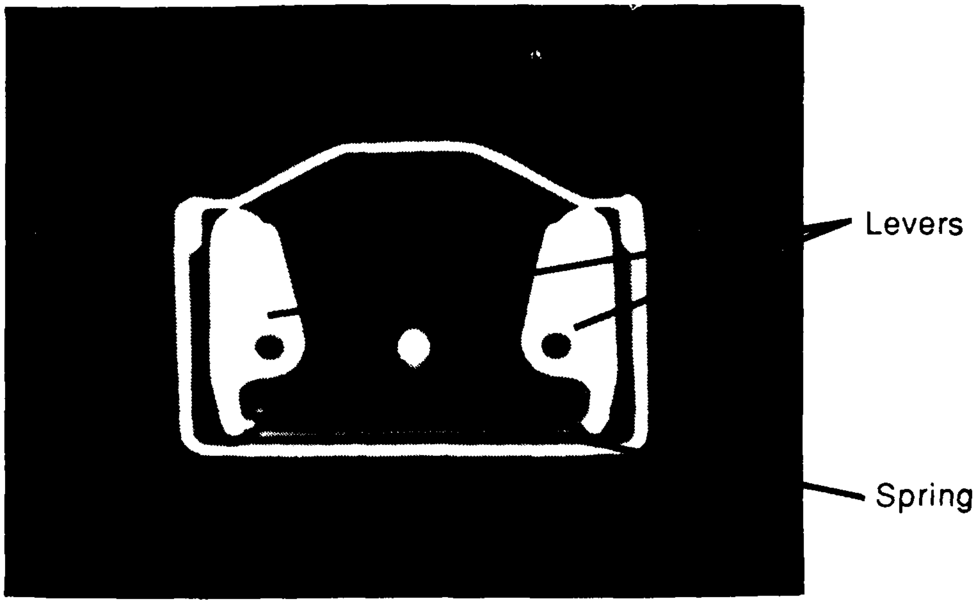


Figure 3.3-5 CT image at scan plane #5 in Figure 3.3-2 for the Figure 3.3-1 switch from System E

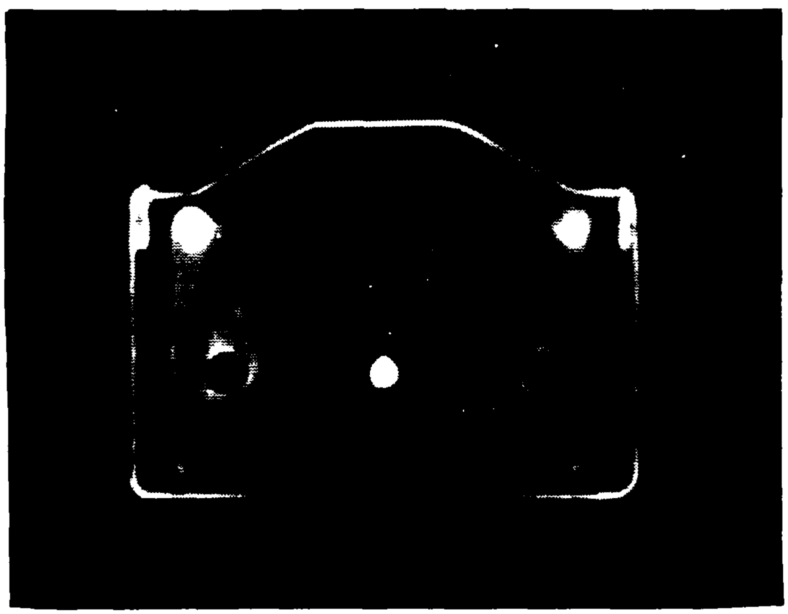


Figure 3.3-6 CT image at scan plane #5 of Figure 3.3-2 for the Figure 3.3-1 switch from System C

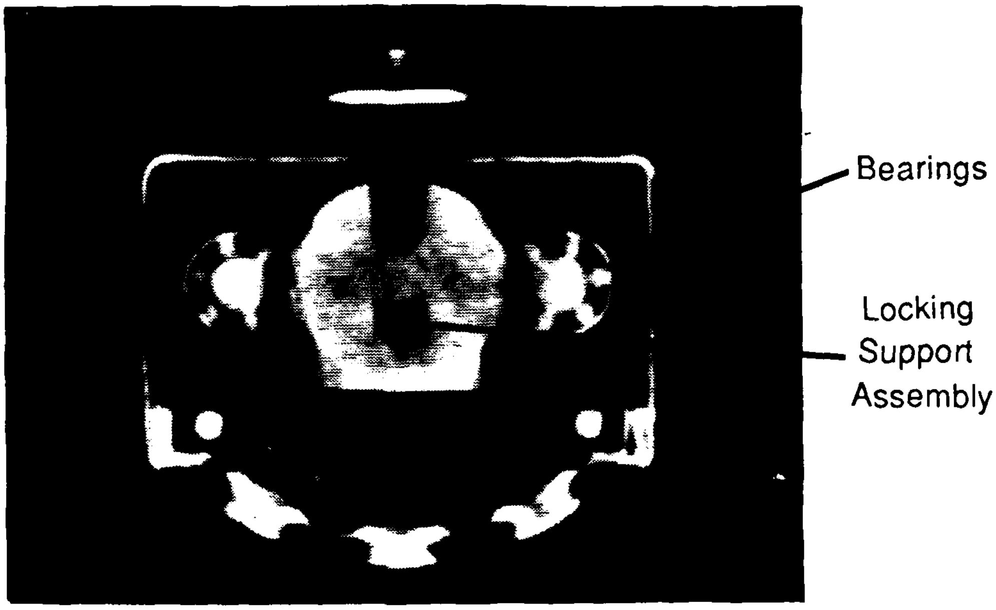


Figure 3.3-7 CT image of Figure 3.3-1 switch from System C

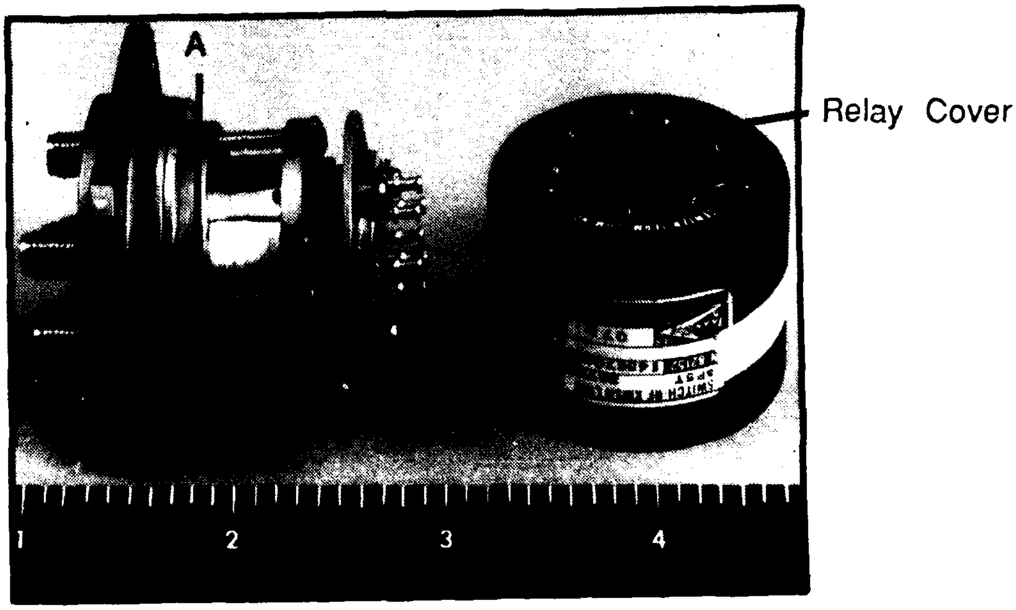


Figure 3.3-8 Military grade multi-pole RF relay

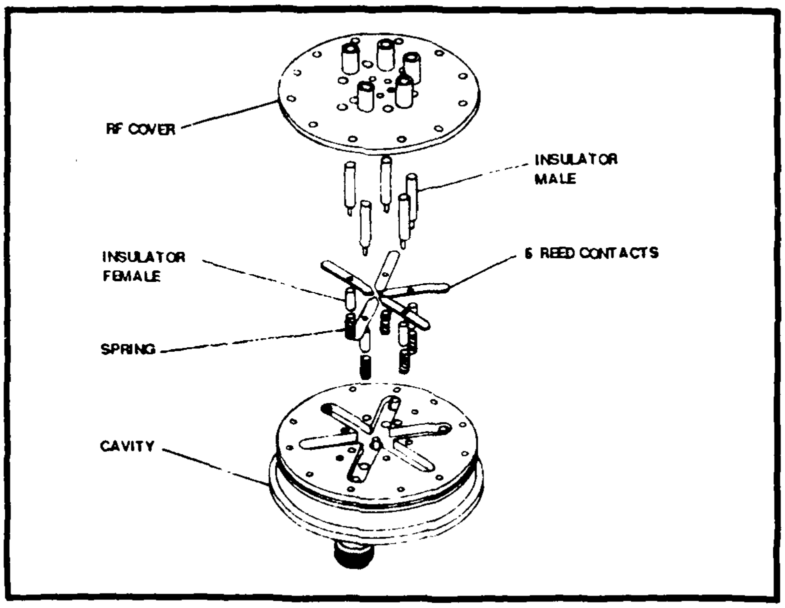


Figure 3.3-9 Exploded view of the multi-pole RF relay; note 5 reed contacts are used

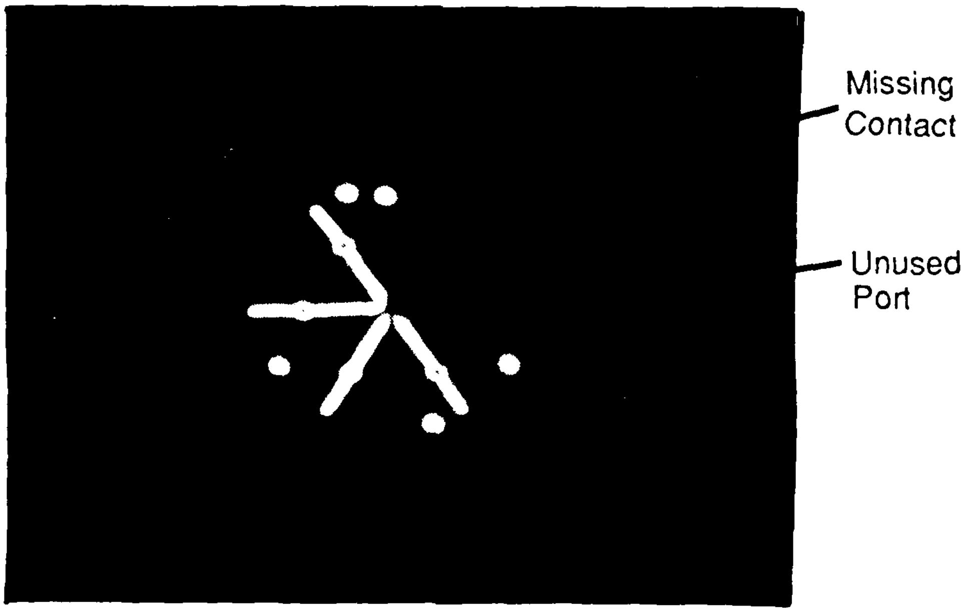


Figure 3.3-10 CT scan of the Figure 3.3-8 RF relay showing 4 good contacts from System E

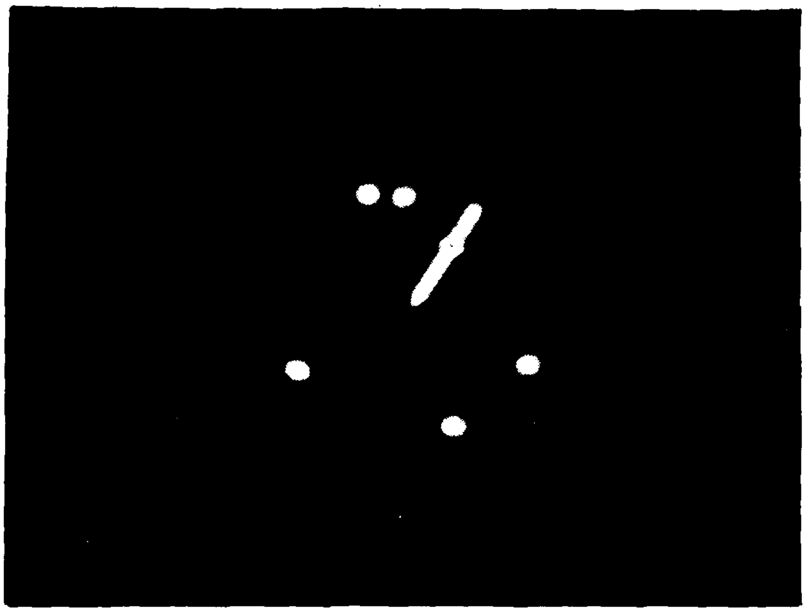


Figure 3.3-11 CT scan of the Figure 3.3-8 RF relay showing bad contact from System E

3.4 Connectors

Connectors are mechanical interfaces in the transmission of electrical information that are liable to cause a mission failure. Reliable connectors are essential because of this criticality issue, but no matter how carefully they are designed and manufactured, their life is limited. Some of the most critical situations can be found in the use of connectors in umbilical cables (on missiles and rockets, IUS, Shuttle etc.), where their failure to release could immediately wipe out the mission without a chance for recovery. Other highly critical situations involve power supplies, high-temperature engine harnesses, avionics, circuit boards, and component sockets.

Military connectors have some of the highest production standards required, yet failures continue to occur, sometimes due to manufactured defects. For example, a cylindrical multipin connector may use a mineral-filled phenolic to support the contacts. One suspect failure mode is in the integrity of the phenolic and its density between the pins. Should a void reside between pins, it may allow the conductivity to increase in that region providing a path for an electrical short to occur. Other issues involve the soundness of the mechanical support structure (i.e., welds, press fits) and contacts (i.e., position, crimp quality) during vibration and environmental testing. Destructive analysis after a failure is often difficult, costly, time consuming, and does not always yield correct information.

Military grade connectors range in cost from $20 to $8,000+ where criticality to the mission is a driving function for cost. Connectors come in all shapes and sizes, and range from handling a single wire to those which handle several hundred wires of varying sizes and shapes (coax, RF, fiber optic, etc.). CT was applied to the inspection of connectors to determine internal dimensions, phenolic integrity, pin alignment and integrity, and other structural features.

3.4.1 RF Cable and Connector

Data and voice communications are often transmitted at radio frequencies (RF) where generally the higher the frequency, the higher the tolerances and cost of the components. Figure 3.4-1 is a mission-essential 18 Ghz RF cable used in a major military program and has a cost of approximately $2000. A nearly impossible measurement to make is whether or not the dielectric Teflon is compressed when a connection is made to the cable connector. Note in Figure 3.4-1 that the connector A has an expansion adaptor B fitted to it. Compression of the Teflon could alter the impedance of the cable, which would degrade performance of the carefully designed component.

Current inspection methods for the connector involve lot sampling. This is a costly sectioning process whereby the connector is mounted in an acrylic potting compound, sectioned with a saw, and polished. This same analysis sectioning was performed nondestructively using System B where an axial slice was taken across the connector and is shown in Figure 3.4-2.

Reproduction has reduced the visibility of detail that was present on the original display monitor. The steel shell did not prevent the system from obtaining remarkable detail of several internal structures. In the center is the pin where individual strands of the center wire can be identified to the left. Direct center is an

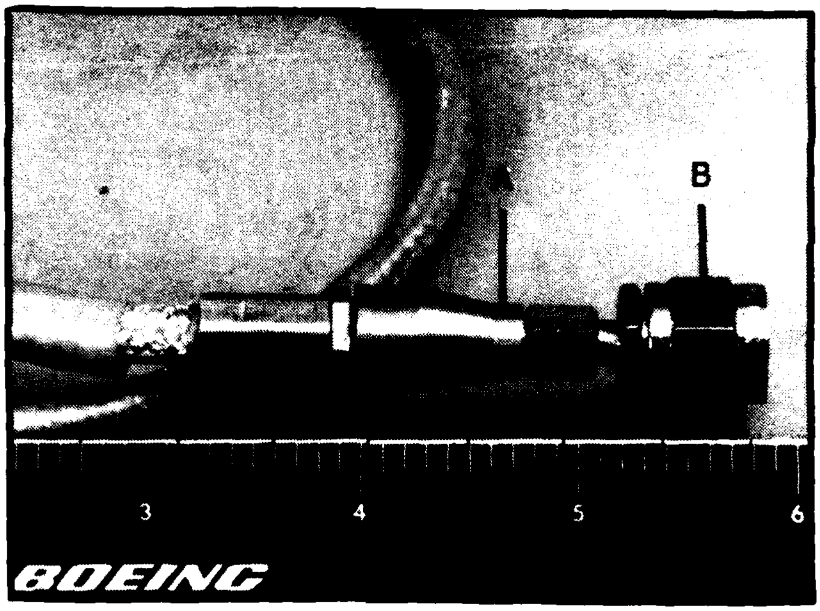


Figure 3.4-1 RF cable and connector with expansion adaptor

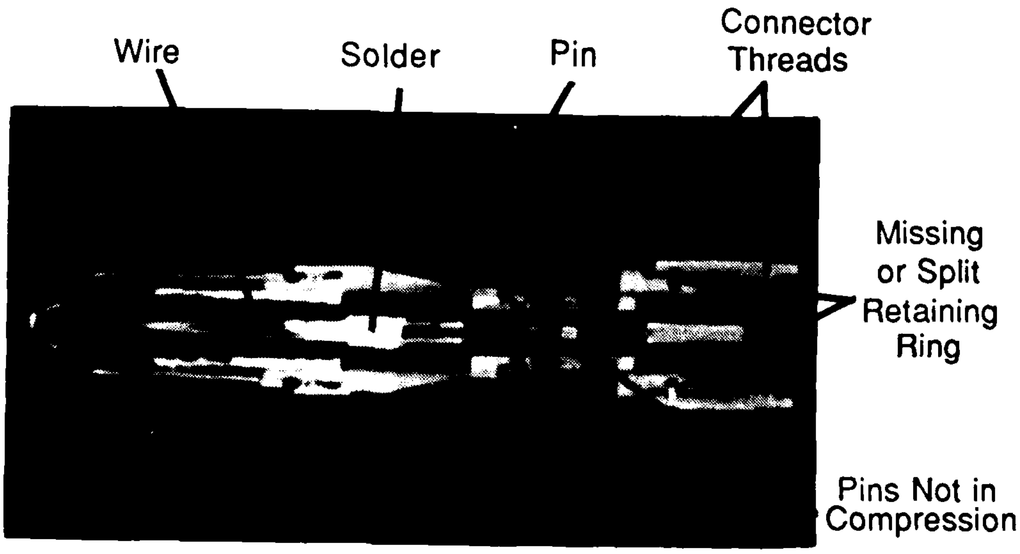


Figure 3.4-2 CT axial image of the Figure 3.4-1 connector from System B

indication of the amount of solder connecting the wire to the pin. Details of the connector threads can be seen (above and below) on both the large and small terminal connections. A gap to the right of the pin (not observable in this photo) between the dielectrics of Parts A and B indicate that the Teflon is not being compressed. Other features such as hermetic rubber rings and retaining rings are also clearly shown.

3.5 Miscellaneous Components

The categorizing of all possible electrical components qualified for CT inspection into four categories tends to oversimplify the issue. Other components inspected include an aircraft external temperature probe, discrete microwave transistors, a capacitive filter, a fiber optic wavelength division multiplexer, ceramic DIP hermetic seals, a pressure transducer, a plastic circuit breaker, and large cable (00 and 000 gauge) splices. Components which were desired but were unavailable or beyond the limitations of CT include rotary fiber optic sensors, electrical actuators, fiber optic connectors, and a flight ready aluminum box containing electronic components. Of the components that received at least one scan, several deserve further consideration for CT analysis based on their individual criticality and payback. The temperature probe was one of the more interesting components investigated.

3.5.1 Aircraft Temperature Probe

All commercial and military aircraft (along with several missiles such as ALCM) are equipped with some version of the total temperature probe shown in Figure 3.5-1. This component is critical to the avionics of the mission and is hermetically welded steel. A digital radiograph taken on System E, shown in Figure 3.5-2, shows a complicated arrangement of electrical components in the temperature probe. A cross-sectional slice of the sensor inlet in Figure 3.5-3 locates the sensor element in the center at the base of the curved inlet.

The image reveals density variations in the inlet structure and mechanical or welding voids near the base of the sensor left of center. Figure 3.5-4 is a scan taken in location #5 in Figure 3.5-2 and identifies what appears to be 3 diodes (2 vertical, 1 horizontal). Figure 3.3-5 shows a contrast adjustment from Figure 3.3-4 which reveals the hollow connector pin, the structure supporting the pins, and a 5-pin component socket. Figure 3.5-6 shows a scan taken in location #7 which clearly identifies 9 nuts supporting the circuit board arrangement.

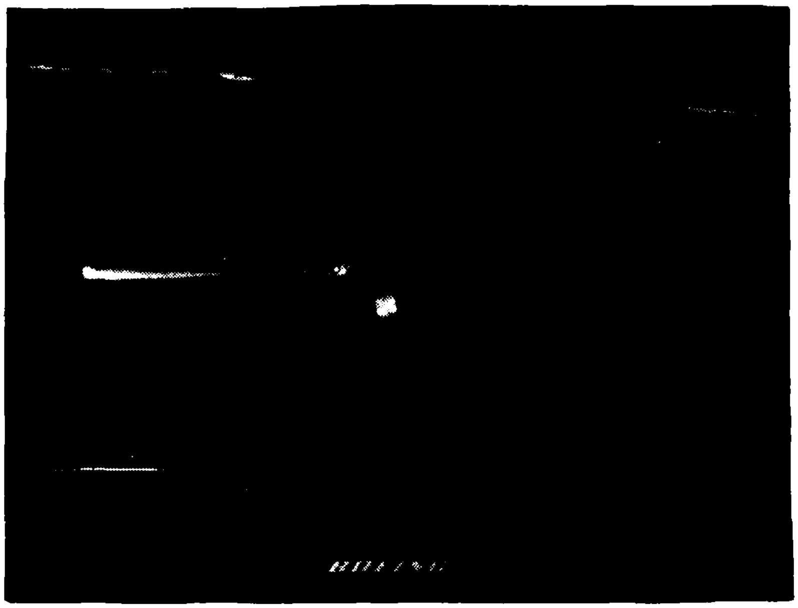


Figure 3.5-1 Aircraft and missile temperature probe

Scan Locations: 7 5

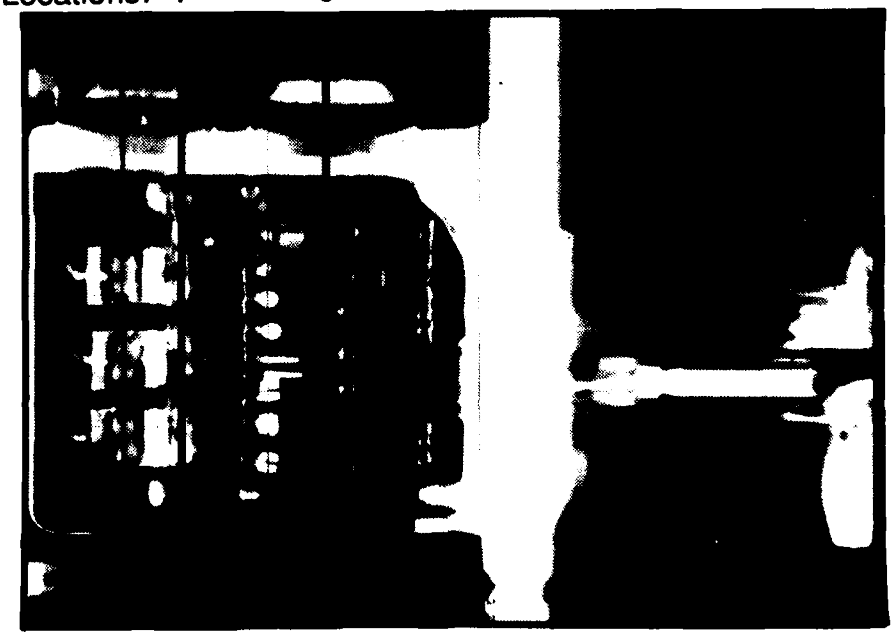


Figure 3.5-2 Digital radiograph of the Figure 3.5-1 temperature probe from System E

Figure 3.5-3 CT image of the Figure 3.5-1 temperature probe from System E

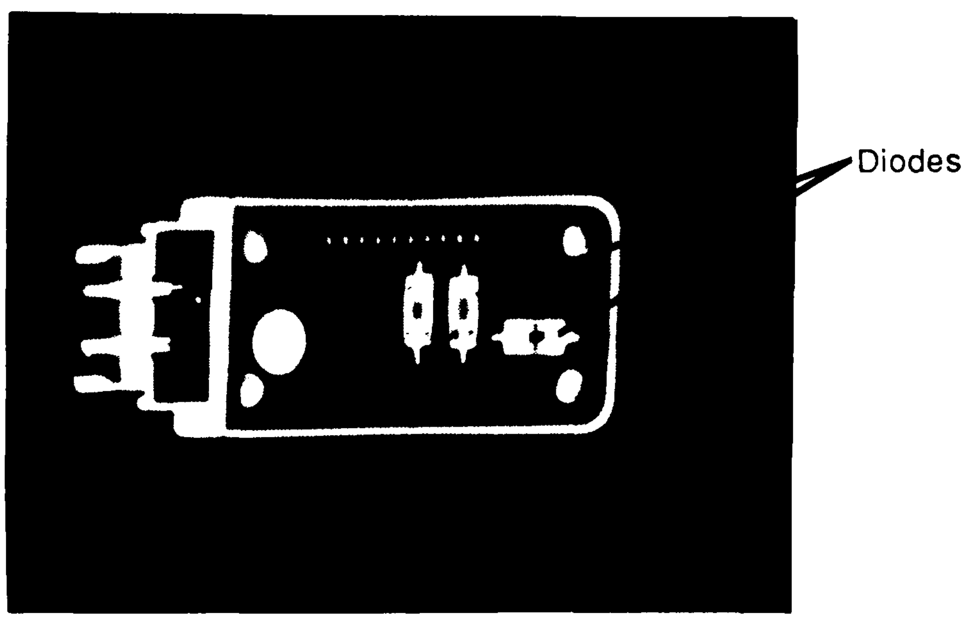


Figure 3.5-4 CT image at scan plane #5 of Figure 3.5-2 from System E

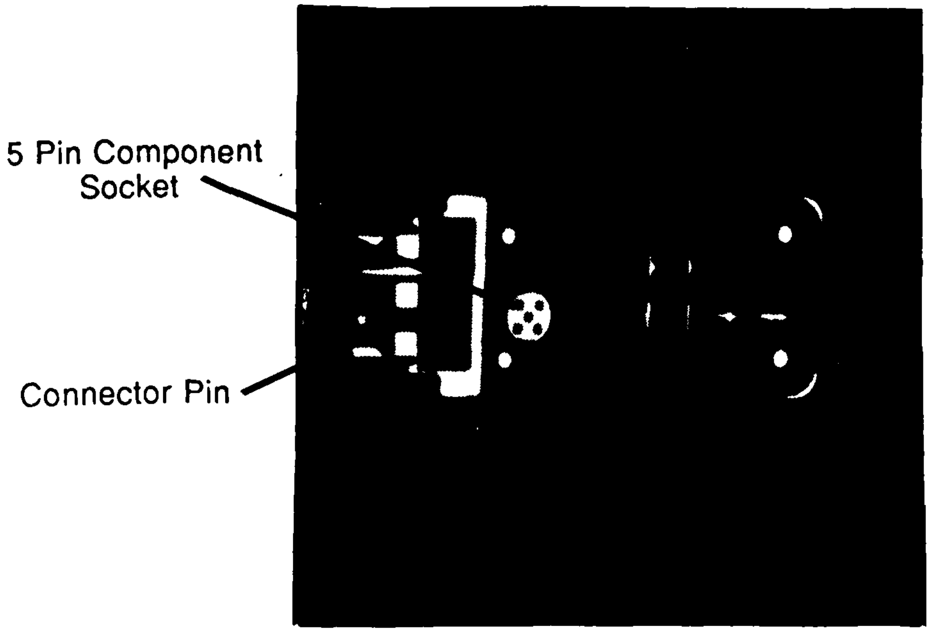


Figure 3.5-5 CT image at scan plane #5 with contrast adjustment from System E

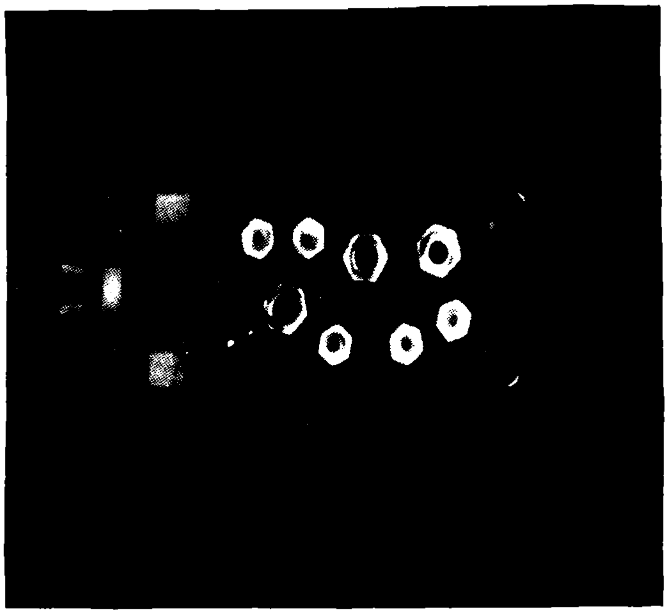


Figure 3.5-6 CT image at scan plane #7 of Figure 3.5-2 from System E showing 9 nuts supporting the circuit boards

4.0 COST BENEFIT ANALYSIS

A primary objective of the CTAD program is to assess what economic benefits are obtained from CT scanning a component. Furthermore, if CT proves viable in component inspection, then what is the minimum cost required to obtain the necessary information to yield the highest payback. It must be pointed out, however, that economic benefits can be realized in more ways than by producing a less expensive component or by having a less expensive inspection method. Economic benefit can also be realized from increased component performance and higher component reliability - especially for mission-critical components.

Two general areas of inspection that could have potential payback for CT inspection are identified in this study: production inspection and failure analysis. The production inspection aspect appeals to the large-volume, high-value items that have inadequate or high-cost inspection. The circuit board solder evaluation fits this category. Failure analysis inspections are low volume. The economic payback for failure analysis inspections would come from evaluating failure mechanisms in mission-critical components, where cost of the component may be very low compared to the cost of the mission. The application of CT at the depot level for periodic inspection to assure quality of the stored components could fit either area with similar analysis. This "first look" at economic payback examined during this preliminary testing task is based on purchasing CT scan time and the usefulness, or relevance, of the data obtained.

4.1 Cost Benefit of Circuit Board Inspection

The inspection of circuit boards for solder defects using laminography has been shown to be viable for defect detection. The viability from an economic perspective is a function of the inspection costs and throughput of the laminographic approach versus the currently accepted approach. A laminographic system designed for high throughput is estimated to cost in the range of $500K and is able to inspect a typical board in about 15 minutes. Figure 4.1-1 shows a rough estimate of the economic factors of using the laminography system and of the required throughput of boards necessary to achieve payback in 2, 3 and 5 years. This rough estimate is based on replacing a one hour visual inspection on 100 percent of the boards and a 3.5 hour X-ray examination on a 5 percent lot sampling. The savings is expected to be around $69/board. The laminography approach actually improves the overall inspection reliability by providing 100 percent examination with X-rays. A cost benefit factor for improved inspection reliability is not included in the Figure 4.1-1 results. The figure indicates that a throughput of 17 boards/shift would be needed for a 2 year payback and 9 boards/shift for a 5 year payback.

4.2 Costs of CT versus Destructive Failure Analysis

The Failure Analysis group in Boeing is a crucial element in solving difficult engineering problems as well as facilitating the sale and delivery of military hardware. Programs devote a fair portion of their design budget to the destructive analysis of new components. For example, the transformer in Figure 3.1-6 had 200 labor hours budgeted for its destructive analysis.

The destructive evaluation of connectors can range from simple sectioning to a detailed analysis (e.g., a multipin connector down to each contact) including evidence of particulate matter and corrosion. On the average, the cost of a destructive analysis will range from 120 to 1800+ percent of the component cost. For inexpensive components the cost of destructive testing can be many times the cost fo the component, i.e., inspection cost is a high percentage of the part cost. The cost of destructive testing on more expensive components will be a smaller percentage of the inspection cost; additionally, an expensive part is sacrificed. Depending on the inspection criteria, an optimized CT inspection could represent a savings by replacing a majority of the destructive tests. CT testing is estimated at only 10 to 800 percent of the component cost for the types of parts examined in this study.

	2 Years	3 Years	5 Years
Machine Cost	$500,000	$500,000	$500,000
Cost of Money (@ 7%)	$ 72,455	$ 112,522	$ 201,276
O&M	$ 60,000	$ 90,000	$ 150,000
Total Cost	$ 632,450	$ 702,522	$ 851,276
Total Cost/Year	$ 316,225	$ 234,174	$ 170,255
Savings/Board @ $75/hr Labor Rate	$ 69	$ 69	$ 69
Board Throughput/Yr. Required	4583	3394	2467
Boards/8 Hr. Shift (1 shift/day)	17	13	9

Figure 4.1-1 Estimated throughput of PC boards to achieve economic payback for a production laminography system

The costs of destructive evaluation of switches and relays range from 200 - 3500+ percent of the component cost. The RF relay in Figure 3.3-9 had a problem which required 2 person-years to solve. After viewing the images in Section 3.3, a manager of the program stated that CT would have been instrumental in helping solving their problem and, if successful, would have shown a substantial cost savings.

The fact remains that the time and effort (and therefore cost) expended by Failure Analysis groups in industry is significant. The costs for a typical destructive failure analysis by Boeing Aerospace was approximated and is illustrated in Figure 4.2-1. The relay which underwent failure analysis is shown in Figure 4.2-2. The relay example in Figure 4.2-1 shows that approximately $1800 was spent on evaluating a $50 component; destructive inspection relative to the component cost is ~3600 percent. The CT inspection of switches and relays is estimated at a cost range of 20 - 800 percent of the various component costs. This represents a significant savings.

Failure Analysis Process for a Typical Relay

Component: Miniature Circuit Board Can Relay
Component Cost: $50
Case Dimensions: 5/16" dia. x 3/8"
Suspected Failure: Welded Contacts

	Tests and Processes	Time	Approx. Cost
1.	Electrical Testing	1 hour	$ 95 *
2.	Package Gas Analysis	3 days	$100 Δ
3.	Hermetic Seal Test	4 hours	$ 380*
4.	Open Package	3 hours	$ 285
5.	Full Analysis	8 hours	$ 760*
6.	Document Results	2 hours	$ 190*

Total Analysis Time: 18 hours company time
3 days outside vendor analysis
Total Duration: Approximately 1 Week

Approximate Total Cost: $1800

Determined Failure: Welded Contacts

* Costs distributed as 40percent shop time and 60percent engineering time.
Δ Performed by an outside vendor.

Figure 4.2-1 Typical failure analysis costs for a relay

Whereas the detailed analysis of certain components is mandatory and well worth the effort, as the example shows, there are undoubtedly some components which

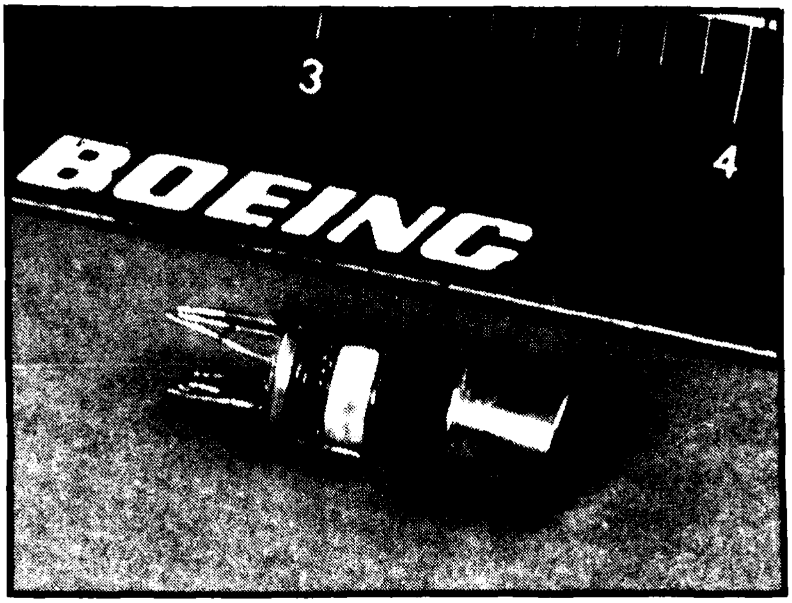


Figure 4.2-2 Relay analyzed by failure analysis

are questionable as to whether the information is worth the expense. The relay example of Figure 4.2-1 was scanned on System B to identify the welded contact, and while the resolution failed to clearly distinguish the welded contacts (the contacts are approximately 0.4 mm [0.016 inch] thick), analysis of the scans inferred that there was a weld.

It is conceivable that the analysis of this relay could have been conducted on an optimized CT system in less than 1 day for a cost of approximately $500, yielding the same results as destructive analysis (but for $1300 less). While the analysis cost for such inexpensive components is desired to be much less, the CT inspection method would still show a cost savings over the present method with an added benefit: preserving the evidence.

5.0 RECOMMENDATIONS FOR FURTHER ANALYSIS

The overall recommendations for follow-on investigation of electronics would be to concentrate on circuit board problems, but continue to be open to possible investigation of all components which are used in mission-critical or mission-essential situations. The use of higher resolution CT systems in further studies is necessary for understanding the applicability of CT to electronics.

5.1 Transformers and Magnetic Cores

Presently, costs of destructive inspection for transformers range from 120 percent - 200+ percent of the component cost (that is the cost of the destructed component plus analysis expenses). CT inspection with current technology could perform all but the microcracking detection for an estimated $2500 - $3500 per component. On a $5000 transformer this represents a considerable savings over destructive testing techniques. Inspection using an optimized CT system could greatly reduce the costs to 10 percent - 80 percent of the per component cost (figures based upon the two selected transformers). Thus, a $5000 component could be inspected for $500 (10 percent of component cost).

Out of a total of 5 transformer components scanned, the steel E-core and the ferrite core transformers (Section 3.1) provided more useful information in terms of CT ability to offer some measurable payback. Both transformers are examples of typical components used in mission-critical and mission-essential applications and are worthy of additional analysis. Analysis might include scans on the high-resolution CT systems coupled with destructive metallurgical analysis to verify the results. The issue of the importance and ability to detect microcracking needs to be resolved. In relation to the rest of the components analyzed in this task assignment, transformers were ranked second to circuit boards for immediate follow-on inspection analysis.

5.2 Circuit Boards

The inspection of circuit boards for solder integrity is an increasing problem for industry. Recent military and industrial specifications are calling for more and better inspections. X-ray radiography is currently performed to determine joint integrity. This technique has been proven quite effective in the study of single-sided boards, but double-sided boards add a new twist to the inspection. Double-sided boards containing solder pads over the same location further increase the difficulty in assessing bond integrity and locating solder balls. This limits the usefulness of traditional radiography. So that despite the precautions taken to inspect for bond integrity, bond related defects can be expected to go undetected unless an improvement in the inspection technique is found.

The recommendation for further analysis is to fully explore the abilities of CT and laminography in the evaluation of solder bond integrity in circuit boards. The analysis should include several correlations between CT and laminography data with metallurgical evaluations on various types of defects and materials. This evaluation will not only serve to form a more complete understanding of the feasibility of inspection on circuit boards and its place in the production process, but will provide the system developers the necessary feedback to assist in solving the industry wide problem. As part of this analysis, the use of CT or laminography to reverse engineer the traces on multilayer boards should be investigated.

5.3 Switches and Relays

Further analysis of switches and relays could be interesting, but the immediate inspection needs are not as predominant as those of circuit boards. The recommendation for the inspection of these components is for analysis to continue only in the case of special units that may be brought to the attention of the program and that are mission critical and mission essential.

5.4 Connectors

The inspection performed on 2 of 4 connectors provided useful information; however, time and system constraints prevented all of the connectors from being fully evaluated. One of the main physical constraints for scanning connectors is that the optimum setting is to examine connectors with the wires still attached. For this application, industrial scanners with mid-energy-level capability that rotate about the object (like a medical CT system) are needed. Connectors could be placed in the system with the cables attached and would not be stressed by the system motion. Because there is a strong interest in connector integrity, the recommendation is to investigate, on a small scale effort, connectors which are brought to the attention of the program and fill the needs of mission-critical and mission-essential applications.

5.5 Miscellaneous Components

Although there were several components which were qualified for CT inspection, there were no particular components or component categories which clearly stood out as a candidate for further analysis. Of the components discovered, fiber optic connectors and sensors showed a strong need for high-resolution inspection well in the 0.010 - 0.020 mm (0.0004 - 0.0008 inches) region. With the coming of new high-resolution systems it is hoped that CT capabilities will be developed that will allow these items to be tested in the future.

6.0 SUMMARY AND CONCLUSIONS

This preliminary testing task in electronics identified a number of potential candidates for CT inspection such as transformers, circuit boards, connectors, switches and relays. Testing was performed using six commercially available CT systems and one dedicated laminography system. Measurements of CT system capability using resolution and contrast sensitivity test phantoms developed in the CTAD program provided quantitative measures of line-pair modulation and signal to noise ratios. Generally, CT images obtained from systems with the higher line-pair modulation values showed greater detail of interest. The need for higher resolution (better than 4 lp/mm) to image the detail of electronic components was identified as important to the success of the inspection.

This preliminary analysis of a well rounded set of electrical components has recommended that final testing should be pursued in analyzing solder defects on circuit boards using high-resolution CT and laminography. The rough economic analysis indicated that a system capable of inspecting a circuit board in 15 minutes could pay for itself in a few years at 2000 to 4000 boards/year inspection rate. Additionally, failure analysis studies of electronic components were found to be expensive and CT demonstrated the potential of offering an economically viable alternative to destructive testing.

APPENDIX

CT PHANTOMS

A set of CT phantoms was developed for the CTAD program in order to provide consistent evaluation of results from various CT systems. The phantoms serve several purposes. First, they provide a quantitative measure of the CT machine capability that can be used repetitively to assure consistent performance. Second, the quantitative measurements can be used in conjunction with part images to assess a quality level necessary to achieve desired detection or measurement levels in the inspected parts. Third, the phantoms can be used to select CT systems based on the desired sensitivity level for the CT application.

The use of phantoms for CT is complicated due to the wide range of parameters in any CT inspection. Therefore, caution must be used in extrapolating phantom data to suggest a "best" overall CT system. In fact, CT systems have varying designs that result in a range of performance characteristics. The phantoms allow the user a quantitative measure of quality level that, combined with other operating parameters, may suggest an optimum system. While the phantoms used in this program measure line pair resolution and contrast sensitivity, there are several other important parameters a user must be concerned with in selecting a machine for scanning: scan time, field of view, object penetration, data manipulation, system availability and cost.

Three basic phantoms types have been constructed. They are: line pair resolution phantom, contrast sensitivity phantom and a density standard phantom. The resolution and contrast sensitivity measurements are fundamental measures of a system. The density measurement is more of a calibration.

A1 Resolution Phantom

Figure A1-1 shows the line pair resolution phantom. The phantom consists of sets of metallic and acrylic plates of specified thicknesses. Line pairs of 0.5, 1, 2 and 4 lp/mm are formed by the phantom.

The entire assembly is bolted together and the line pair plates can be changed if additional or a different range of line pairs is desired. Following CT scanning the reconstructed image is analyzed by measuring the modulation of the CT numbers resulting from a trace across the line pairs. The modulation at each line pair set is measured as a percentage of the modulation, where the modulation measured between the 3 mm (0.12 in) thick metal and 3 mm (0.12 in) thick acrylic steps is 100percent. Operating parameters such as field of view, slice thickness, integration time and detector collimation will affect the results. It is desirable to obtain data at CT machine parameters that are the same as that used for part scanning. The resolution phantom has been fabricated in two forms, steel/acrylic and aluminum/acrylic. The steel/acrylic phantom is for systems of 300 kVp and up, the aluminum/acrylic phantom is for systems under 300 kVp.

Figure A1-1 Photo of the resolution phantom

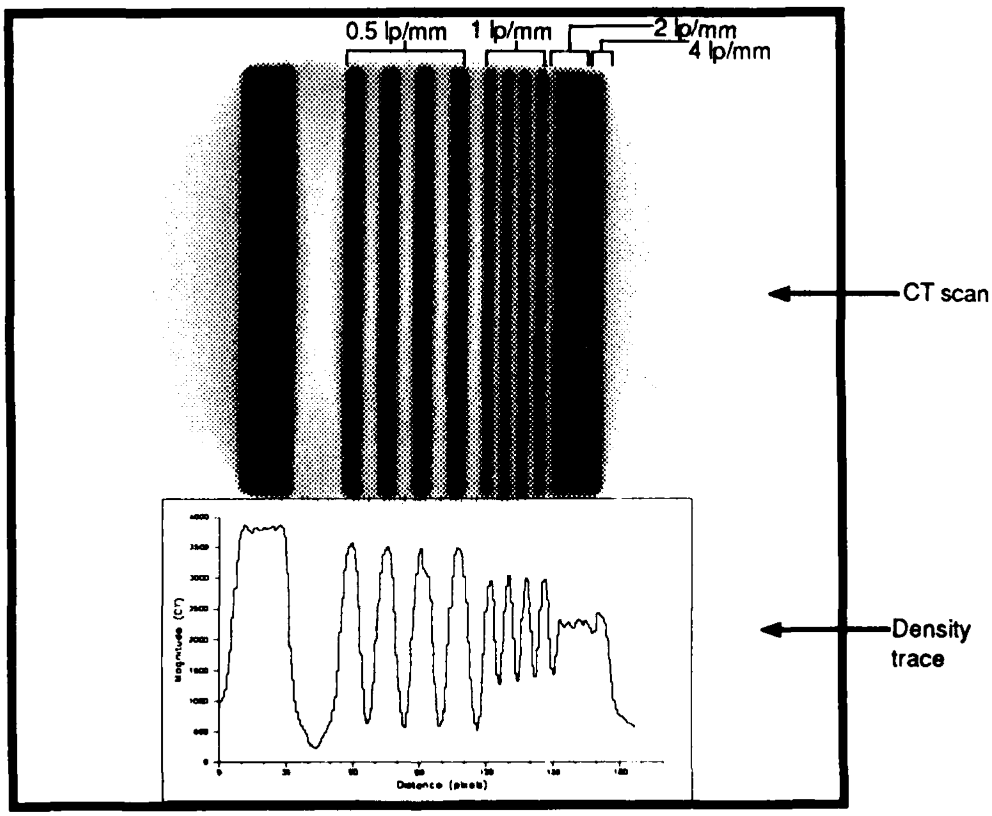


Figure A1-2 CT slice taken on the resolution phantom

Figure A1-2 shows a CT image of the steel resolution phantom obtained from a high-resolution CT machine. The CT image density contour line across the gauge indicates modulation for the respective line pair measurements at approximately 82 percent at 1/2 lp/mm, 46 percent at 1 lp/mm, 4 percent at 2 lp/mm, and 0 percent at 4 lp/mm.

A2 Contrast Sensitivity Phantom

The contrast sensitivity phantom is a uniform disc of aluminum, 25 mm (1 inch) thick. Two sizes were made, one is 140 mm (5.5 inch) in diameter and the other is 70 mm (2.76 inch) in diameter. The smaller diameter size is used on systems with small fields of view or low kVp. Figure A2-1 shows an example CT slice of the large aluminum contrast sensitivity phantom with the corresponding density trace.

The measurement of contrast sensitivity is obtained by taking a region in the reconstructed image and determining the average and standard deviation for all CT numbers in the region. A typical region size of 1 cm (0.39 inch) diameter is used. Readings are usually taken at the center of the disk. The ratio of the average to the standard deviation is used as a signal to noise measurement. The inverse is a measure of contrast sensitivity. The signal to noise measurement for the density trace shown in Figure A2-1 is approximately 6.

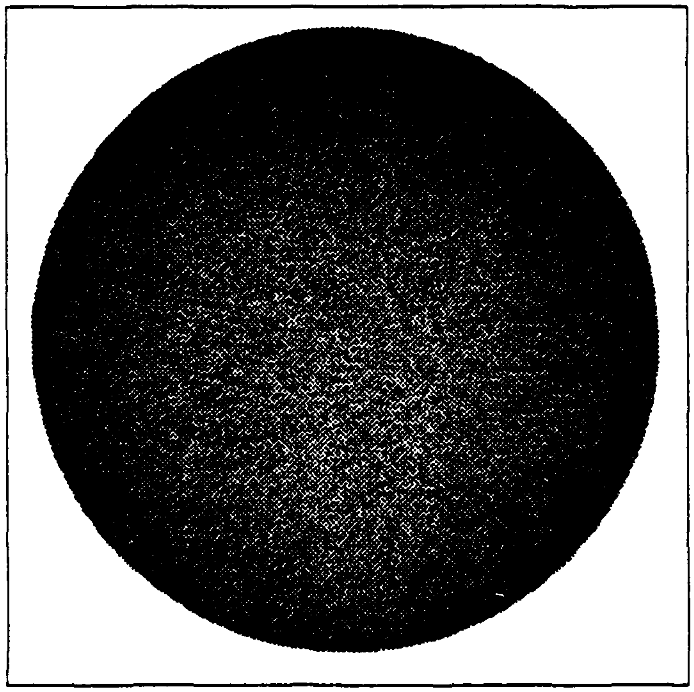
The signal to noise ratio measurements are an important measure of system performance. The values improve with higher signal strengths. They also improve with smoothing algorithms in the reconstruction; however, this will decrease the resolution. Thus, the signal to noise and resolution must be considered together in assessing a quality level for performance.

A3 Density Calibration Phantom

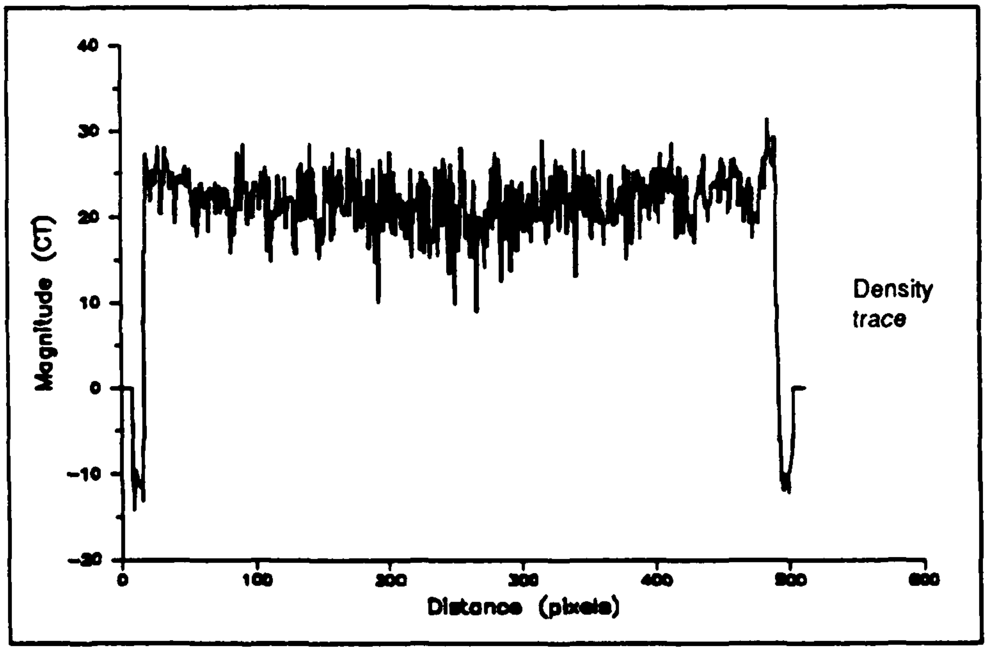
The density calibration phantom is shown in Figure A-2. It consists of an acrylic disk of 140 mm (5.5 inch) diameter with inserts of ten various materials.

The CT numbers for each insert from the reconstructed image are plotted against the known densities to serve as a calibration curve for the machine. The insert materials vary in atomic number which adds another variable in the process when the X-ray energy is such that the photoelectric effects are significant. Nevertheless, the phantom is useful for indicating the general density sensitivity and accuracy of a CT machine. A CT scan of the density calibration phantom is shown in Figure A3-2.

The calibration plot for a 420 keV CT system is shown in Figure A3-3. The CT number (or density), averaged over a small region in the center of the insert, is plotted along the horizontal axis and material density along the vertical axis.

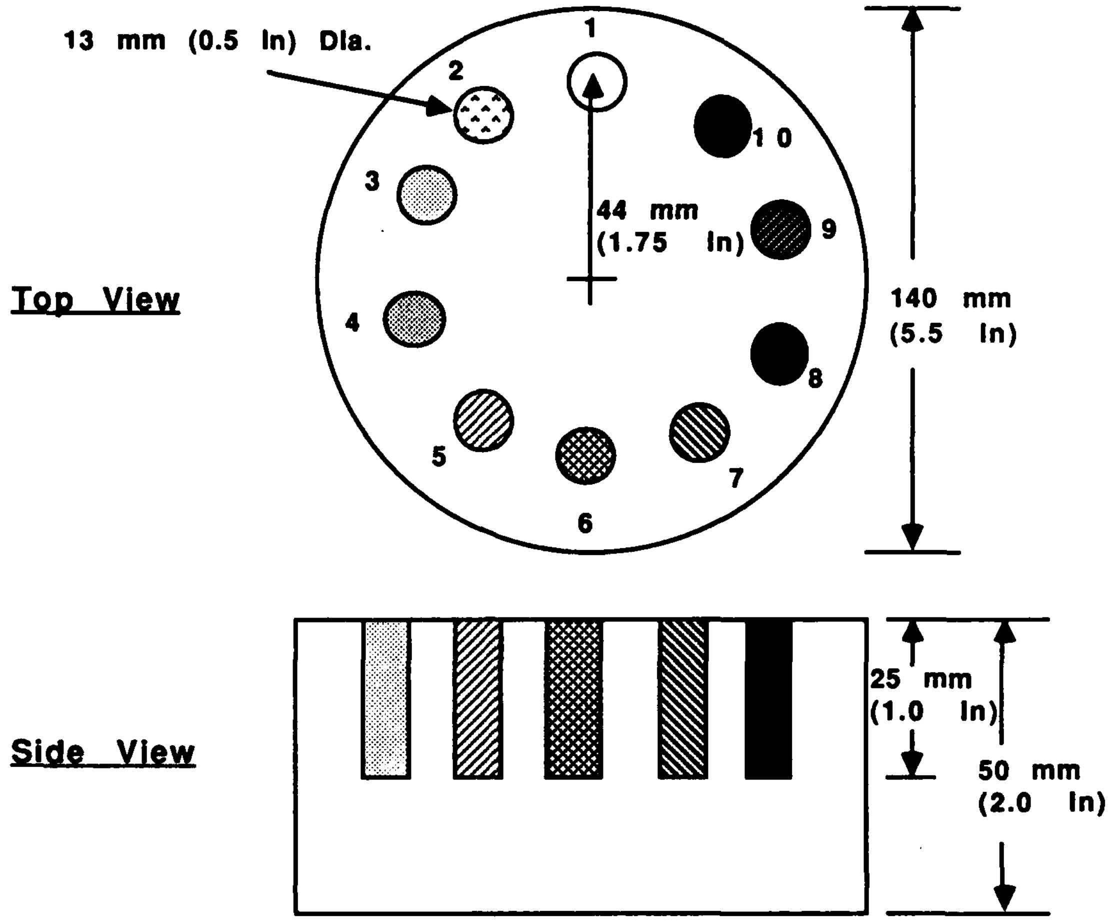


CT scan



Density trace

Figure A2-1 CT slice of contrast sensitivity standard



Each density phantom is a cylinder measuring
13 mm (.05 in) dia. x 25 mm (1.0 in) +/- .0025 mm (0.001 in)

The cylinders and their corresponding densities are listed below.

	Material	Density (g/cc)
1	Air Gap	
2	High Molecular Weight Polyethylene	0.945
3	Nylon	1.156
4	Nylatron	1.165
5	Acrylic Plexiglas (core material)	1.193
6	Delrin	1.507
7	Magnesium	1.784
8	Teflon	2.179
9	Aluminum	2.704
10	Titanium	4.423

Figure A3-1 Density calibration standard

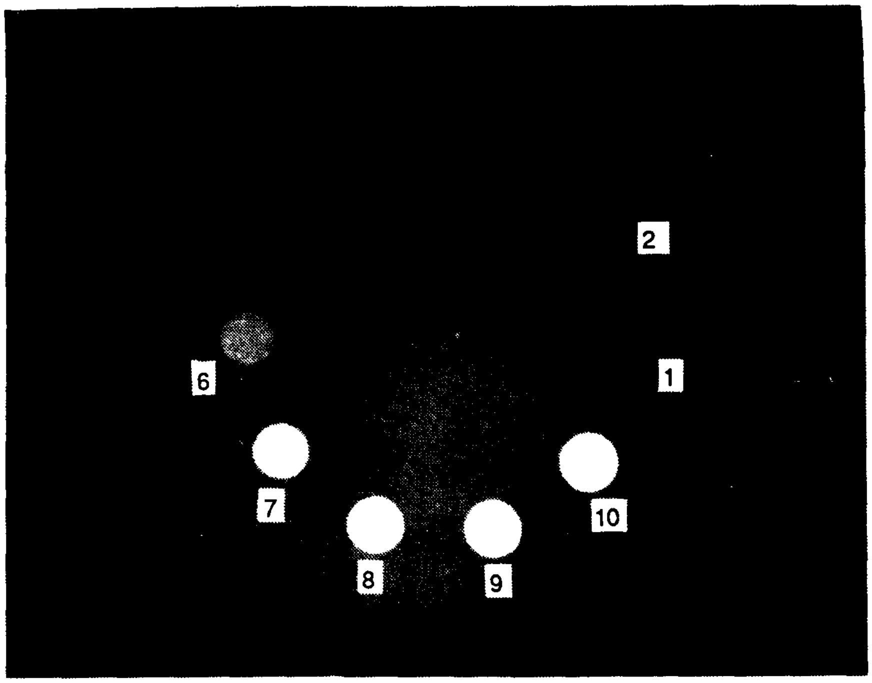


Figure A3-2 CT scan of density calibration phantom

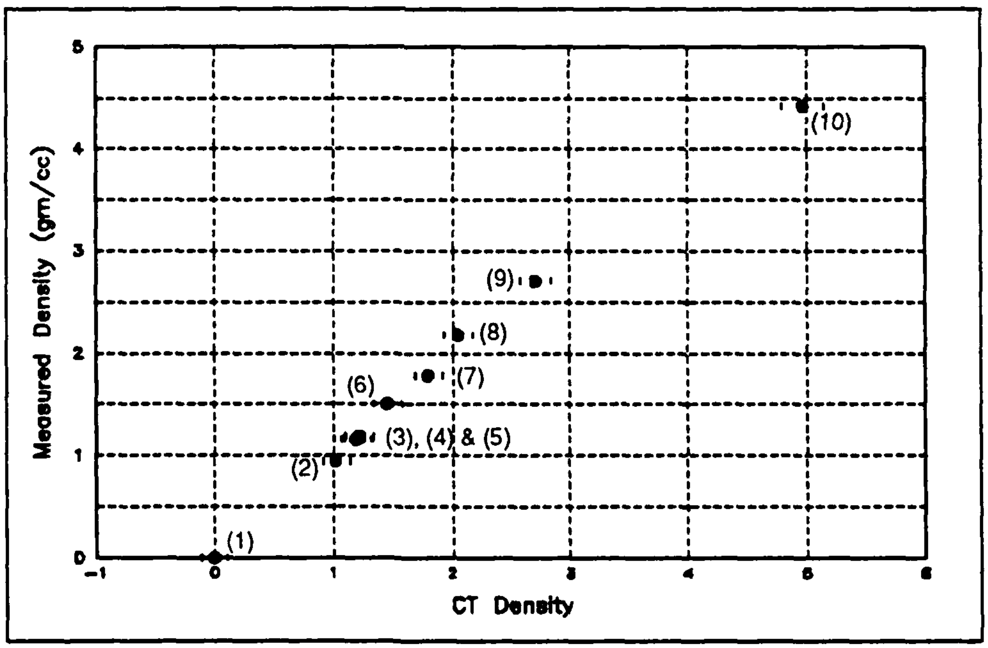


Figure A3-3 Calibration plot for density phantom